

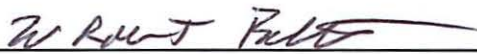
MODELING CHANGES IN THE LENGTH OF THE AGRICULTURAL GROWING SEASON IN

INTERIOR ALASKA

By

Nicole Y. Swenson

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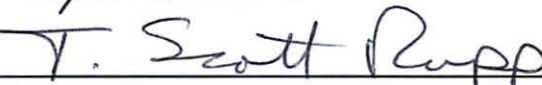
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MODELING CHANGES IN THE LENGTH OF THE AGRICULTURAL GROWING SEASON IN

INTERIOR ALASKA

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By

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Abstract

Food security is a growing global concern as population growth continues in a period of rapid climatic change. The amplification of climate change and dependence upon imported foods at high latitudes makes Alaskans especially vulnerable to both global and local changes. Although many climate impacts present challenges, rising air temperatures could provide economic opportunities for Alaskan agriculturalists by extending growing seasons. Future growing season length has previously been estimated, however these estimates did not explicitly account for the constraints of agricultural systems. This research explores the relationship between air temperature, soil temperature and growing season length in agricultural management systems in Interior Alaska to better understand how climate scenarios can be used to identify future opportunities. Air and soil temperature data were collected under four different crop systems and used in combination with historical observations to inform a model that projects *usable* growing degree-days in Interior Alaska to the end of the century. Increases of *usable* degree-days were projected to increase from 33-70% by 2100. The projected increases could increase success of currently marginally successful crops (e.g., canola, corn, and sunflowers). Such opportunities could lead to increased food security, but future planning will require culturally appropriate planning and institutional support.

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Dedication

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Chapter 1

Introduction

1.1 Introduction and Context

Climate change is expected to impact every corner of the globe, influencing all facets of socio-ecological systems in varying ways and at different magnitudes. As average global surface temperatures continue to increase, the Arctic is expected to experience the most rapid and amplified effects of climate change (Walsh et al. 2008). Over the last 50 years, mean annual air temperature in the Interior of Alaska has increased 1.3C, with a disproportionate amount of the warming occurring in the winter (Wolken et al. 2011). High latitude regions are expected to increase 1.5-4.5°C above the current global mean by the end of the century (Euskirchen et al. 2006). In Alaska, anticipated climate change effects include permafrost degradation, altered snow cover, increased ecosystem productivity, shifts in seasonal fire regimes (Rupp et al. 2007; SNAP 2009), altered species distribution, changes in migratory patterns, (Hayhoe 2010; Rosenzweig et al. 2008) and lengthening of growing seasons (Euskirchen et al. 2006; SNAP 2009).

Consequently the global food system, upon which Interior Alaskan residents rely upon for the majority of their food supply, is highly vulnerable to all aspects (physical,

social, and economic) of change including climate/weather, fuel prices and population growth (Juday et al. 2005; Godfray et al. 2010). Increasing local food production in Interior Alaska could reduce the dependence on this vulnerable global system and increase local food security. However currently, local agricultural production is limited due to short growing seasons, cold soils, periodic early frosts (Holloway 1993; Loring and Gerlach 2009), inopportune timing of precipitation events, and low amounts of accumulated heat energy throughout the season (Van Van Veldhuizen and Knight 2004).

The high latitudes (60-90°N), and specifically Interior Alaska, are currently experiencing and projected to continue to face the greatest effects of climate change when compared to temperate regions of the world (Huntington et al. 2005; SNAP 2009). Estimates indicate that by the end of the century winter temperatures in Interior Alaska could increase by as much as 15C, further lengthening the growing season (SNAP 2009). Considering recent observations and projections, rapid climate change could enhance regional agricultural capacity (Juday et al. 2005; Hatch 2011). The residents of Interior Alaska may be afforded the opportunity to capitalize on changing local production capabilities that would reduce their vulnerability to global food insecurity.

Projections of increasing air temperature have already led to speculations that areas of the Arctic may become increasingly practical for larger scale agricultural systems in the future (Juday et al. 2005; Hatch 2011). Currently, agriculturalists in Interior Alaska successfully produce cold tolerant crops including potatoes, cabbages,

broccoli, carrots, beets and barley (Benz and Knopf 2010). Based on an analysis of future scenarios of growing degree-days (GDD), both Juday et al. (2005) and Hatch (2011) suggest the list of feasible crops for the region may be expanded and/or altered to include cash crops such as corn or canola.

Juday et al. (2005) used air temperature thresholds alone to identify seasonal boundaries, ignoring the very important factors of soil temperature and moisture as well as other influential socio-economic factors that can impact the growing season. For example, cool saturated soils in the spring have been identified as limiting factors for many crops (Holloway 1993; Van Veldhuizen and Knight 2004; Loring and Gerlach 2009). Hatch's (2011) study in Interior Alaska highlighted the importance of further data collection and understanding of soil temperatures to identify a way to define the growing season and that includes limiting factors such as soil temperature, moisture, topography, and farm management practices. Predictive models for crop viability and productivity could be greatly improved if accurate soil conditions could be quantified and included in models.

1.2 Thesis Chapter Overview

Chapters 2 and 3 investigate the bio-physical growing season boundaries for Interior Alaska and apply results from local observations to develop a modeling tool that projects growing season lengths and accumulated heat energy (degree-days) available to Interior Alaska agriculturalists through this century. In chapter 2, a two-year dataset

of air temperature, soil temperature (0-15cm) and soil moisture under five different crop regimes is summarized. Based on these observations and historical sources of local climate data and crop management practices, crop thresholds within the growing (0°C) season are quantified using heat energy accumulation values (degree-days). Usable degree-days (UDDs) are then calculated to represent the number of degree-days that are actually available for plant utilization versus the typical total degree-days that accumulate within a season.

Chapter 3 describes the development of a modeling tool that includes future growing season thresholds that are specific to Interior Alaska agriculturalists. The tool provides crop specific estimates of UDDs for use by agriculturalists and decision makers in identifying future crop feasibility as well as potential impacts on current crops and their management systems.

Chapter 4 provides a summary of the research as well as recommendations. As biophysical thresholds influence the productivity of agricultural endeavors, so too do cultural, institutional and economical barriers (Caster 2011; Davies 2008). Relaxing current biophysical boundaries that confine Interior Alaska agriculturalists may not only have profound effects on marginally successful crops but also suggests profound implications on currently successful agriculture practices and crop.

Chapter 2

Quantifying the Usable Growing Season for Interior Alaska Agriculturalists: The Effects of Soil Temperature, Soil Moisture, and Air Temperature on Planting Dates

2.1 Abstract

Projected increases in air temperature in Interior Alaska could change growing conditions considerably. Outside of socio-economic variables, what can be grown in Interior Alaska is limited by a number of factors including, for example, season length, air temperature, soil temperatures and precipitation deficits. In order to assess how changes in climate will affect growing conditions, it is of utmost importance that baseline data be available to discuss the limiting thresholds of agricultural production. Growing degree-days, using air temperatures to estimate seasonal heat accumulation are commonly used to estimate crop feasibility for a given area. However, it is widely thought that cool spring soil temperatures are a limiting factor in crop production in Interior Alaska. Few records of soil temperatures under a variety of cultivated conditions exist for Interior Alaska. This chapter summarizes a two-year dataset of soil and air temperatures under five crop conditions with the objective of documenting the lag between air temperature degree-days and soil temperatures in the spring as well as the heat energy (degree-days) accrued throughout the whole season. Degree-days were accrued between planting date and the terminating frost and consequently termed

usable degree-days (UDDs). The influence of different agriculture vegetation cover types on soil UDDs was examined. In general, crops within management scenarios did not differently affect soil UDDs consistently with the two seasons of measurement. The discrepancy between air and soil temperature in spring (spring lag) was quantified using degree-days and calendar days. Results suggest that a lag of about 90 air temperature degree-days accrue before soils thaw in the spring and 260 and 480 degree-days accumulate before planting date for early field crop and late vegetable crop management scenarios, respectively. Snow melt, soil water content, and daily minimum temperatures emerge as important factors in determining the beginning of the usable growing season.

2.2 Introduction

Soil temperature is an important factor in crop feasibility analyses, as crop germination in the spring and root growth throughout the season requires specific soil temperature ranges to succeed. Soil temperature's influence can be detected in agricultural and ecological systems on daily and annual scales through biological and chemical processes. Critical components of soil health and plant growth such as decomposition, nutrient mineralization, and soil respiration are in part controlled by daily and annual soil temperature cycles (Paul et al. 2004). Soil temperature affects plant growth directly, through physiological responses, and indirectly through its effects on soil nutrient availability such as organic matter decomposition, for example (Paul et

al. 2004). This is particularly important to agriculturalists because soil temperature strongly influences rates of seed germination (Sharratt et al. 2006), seedling emergence and growth, root growth and development, root metabolism, nutrient uptake, water uptake, and microbial activity (Hillel 1982; Scott 2000; Grünzweig et al. 2003; Gliessman 2007a).

Soil temperature is especially important in determining crop feasibility at high latitudes where soils freeze throughout the winter and remain cool after air temperatures have warmed in the spring. In Interior Alaska, it has been assumed that springtime air temperatures usually warm up to optimal growing levels early on, while soils often remain too cold and/or wet to begin planting, because heat transfer is much faster in the air than it is in soils (Hatch 2011; Swanson 2000; Holloway 1993). This phenomenon of air accumulating heat energy before soils in the spring is known as the thermal advantage (Swanson et al. 2000). Determining when the soil is warm enough to plant is especially important for agriculturalists where the length of the growing season is limiting for crop production (Langholz 1989; Van Veldhuizen and Knight 2004).

Every variety of plant species has different soil temperature thresholds for germination and growth (Gliessman 2007a). For example, the individual minimum soil temperature for potato germination is about 8-10°C (Langholz 1989) wheat is 4.7°C and spinach is 2.2°C (ACE 2013). Survivability for perennial crops throughout the winter can be limited by soil temperature (Hatch 2011). Hardiness zones determined by USDA base

the feasibility of perennial crops solely on winter temperature minimums, highlighting the importance of soil temperatures throughout both the summer and winter depending on the crop of interest.

Temperature is a significant factor in determining nutrient cycling and productivity in Interior Alaska Forests (Van Cleve et al. 1990); it is not, however, the sole limiting factor of biogeochemical processes (decomposition, mineralization etc.) in agricultural soils in Interior Alaska. Previous soil temperature analyses in Interior Alaska determined that altering a study area from forest to cultivated fields enhanced soil temperatures, C mineralization and N mineralization (Grünzweig et al. 2003). However, soil temperature was not a significant factor in explaining all soil microbial and biogeochemical differences between agricultural sites. These results highlight that factors such as available nutrients, moisture and agricultural management in subarctic agricultural soils are also contributing factors to agricultural soil health and crop success (Grünzweig et al. 2003).

Soil temperatures are a product of air (ground surface) temperatures, heat flow from Earth's interior, and soil thermal properties (Andersland and Ladanyi 2004). At the most basic level, soil temperatures can be reasonably estimated by air (or ground surface) temperatures and at shallow depths, when ignoring the heat from Earth's core. The overall physical variables that are responsible for ground surface temperature

variations include surface radiative (sunlight), convective flow (surface air masses), evaporation and condensation (Hillel 1982; Andersland and Ladanyi 2004).

Ground surface temperatures undergo an approximate simple periodic (sinusoidal) fluctuation both daily and annually (Hillel 1982; Andersland and Ladanyi 2004; Gliessman 2007a). Although soil temperatures follow the air temperature curve, at depth the amplitude of this sinusoidal curve is smaller than the air temperature curve and the distance between air and soil peaks of the curves are offset. In other words, it takes longer for heat of the air columns to conduct to deeper depths. As air temperature rises at the soil surface, soil temperatures change at varying rates due to these many interacting variables.

Both surface and subsurface characteristics can affect the soil temperature regime. Soil-surface temperature at any single location depends on many variables: air temperature, insolation, wind speed, albedo, topography, soil properties (thermal conductivity, compaction, texture), soil water content and vegetation (Klene et al. 2001). Furthermore, ground temperatures are significantly modified by the effects of soil moisture (Hillel 1982; Scott 2000), soil latent heat, differences in frozen and thawed soils thermal properties, homogeneity of the soil, and the myriad of nonsymmetrical surface temperature influences including snow cover, vegetation type and surface climatic variables (Andersland and Ladanyi 2004).

Although soil temperature is an influential factor in the functioning of ecological and agroecological systems, the thermal regime of Interior Alaska cultivated soils is not well documented. Inquiries throughout the agricultural research history of the Interior including efforts by Sharratt (1993), Grünzweig et al. (2003), and Agricultural and Forestry Experiment Station researchers, University of Alaska, Fairbanks have begun to paint a picture of Interior Alaska's agricultural soil thermal regime.

Low spring soil temperatures have been suggested as a major reason inhibiting Alaskan farms from utilizing all spring air temperature degree-days or having to plant late in the spring (Holloway 1993; Van Veldhuizen and Knight 2004; Hatch 2011). Agriculturalists in Interior Alaska have long manipulated management strategies to alter soil temperatures to meet crop thresholds (Holloway 1993). Soil warming techniques range from aspect consideration, soil mounding, mulches, reflectors, and plastic covers (Holloway 1993). Knowing these parameters, degree-day totals need to be tailored to fit the usable growing season for farmers in order to make projections about future growing seasons. Because of climate change, it is important to explore the potential impacts of increases to spring temperatures in order to plan for future agricultural potential.

This research investigates the relationships between spring air and soil temperature and the resultant impact on planting dates. The effect of different agricultural vegetation / land cover types on soil temperature is examined using

seasonal heating units (degree-days). The objectives of this research are: 1) To measure soil degree-days accrued in an Interior Alaska farm under various cover types; 2) To determine the effects of crops on soil degree-days; 3) Quantify the lag between daily air temperatures exceeding 0°C and planting date to determine how many degree-days accumulate in the spring that are not usable to farmers due to frozen soils, low soil temperatures, or damaging air temperature minimums.

2.3 Methods

2.3.1 Study Site

The experimental site selected for this research was located in the lower fields of the University of Alaska Fairbanks (UAF), Fairbanks Experiment Farm (FEF). FEF is located in Interior Alaska at N 64° 51' 16.66" and W 147° 51' 36.40" longitude and latitude. Fairbanks is the largest urban hub for Interior Alaska. There are less than 4 hours of daylight on winter solstice and more than 22 hours of daylight at the summer solstice (ACRC 2013). This extreme swing in day length results in equally extreme seasonal temperature swings causing Fairbanks to experience on average 10 days below -40°C and 13 days above 27°C (ACRC 2013). The 30 year average (1981-2010) temperature in Fairbanks for July and December are 22°C and -15°C respectively (ACRC 2013). Precipitation is relatively low in the area; the average annual precipitation for

the period of 1971-2000 was 26.26 cm (ACRC 2013). The range in frost free (above 0°C) days vary from 86 to 144 days with a median value of 115 days (ACRC 2013).

FEF fields have been cultivated since its establishment by the USDA in 1906. Historically, large quantities of manure have been used as a nutrient supplement making nitrogen, phosphorus and potassium readily available (Van Veldhuizen and Knight 2004). The FEF floodplain fields contain alluvial soils in the flood plains of the Tanana River and are silt loam in texture at an elevation of 153m (Van Veldhuizen and Knight 2004). There is a relatively a high concentration of calcium carbonate and calcium sulfate salts at the soil surface. These salts are present in the groundwater and are brought to the surface through capillary action as moisture evaporates from the surface (Van Veldhuizen and Knight 2004). The main water table is located 20m below the surface but there is a perched water table on top of the permafrost at about 8m below the soil surface (Van Veldhuizen and Knight 2004).

The selection of this site provided physiographical and geomorphological similarity to other lowland farms in Interior Alaska. The fields are level, which allows for reasonable 'control' or at least equivalency of aspect, snow cover, and soil composition factors, leaving air temperature discrepancies under different vegetation types as the most pertinent independent variable driving soil temperature. The soil characteristics at FEF do not precisely represent each farming location in the Tanana Valley in terms of aspect, slope, soil type and management but was considered representative as baseline

data for the Interior as the last 100 years of agricultural research conducted at FEF has been considered representative of floodplain Interior Alaska growing conditions.

2.3.2 Data Collection and Experimental Design

To calculate the total agricultural growing season degree-days in Interior Alaska, a detailed temperature record was collected to represent cultivated low-lying Interior Alaska soil conditions under different crops in the summers of 2011 and 2012. Five sites were chosen at FEF to represent a different crop or cover type: fallow (bare ground), annual grain, perennial grass, closed canopy vegetable and open canopy vegetable. Multiple varieties of crops were planted in both the 2011 and 2012 collection years due to farm management needs. Varieties were similar in structure so that differences within crop varieties were considered to be negligible and representative of the majority of varieties used in Interior Alaska.

Within each vegetative cover type (crop), plants were uniformly spaced based on the crops usual management practices and planted on the same day. Barley (*Hordeum vulgare*) was planted in a 1m wide swath of 6 rows approximately 15cm apart, resulting in a thick closed canopy (Varieties: Weal Hooded Forage, Finaska Feed, Datal Feed). The perennial crop, smooth brome (*Bromus inermis*), was represented a forage crop under no till management. Smooth brome is referred to as brome or brome grass from hereon. Corn (*Zea mays*) was transplanted at approximately growth stage V2 every

30cm in three rows 45cm apart for 30m. In 2011, the corn variety was Bodacious (*Zea mays* var. Bodacious) and Vision (*Zea mays* var. Vision) in 2012. Potatoes (*Solanum tuberosum*) were spaced in 1m apart, offset diagonally every 1m to create an open canopy cover. Potato varieties used were Cal White (*Solanum tuberosum* var. Cal white) in 2011 and Yukon Gold (*Solanum tuberosum* var Yukon Gold) in 2012.

For this analysis crop types are conceptually broken into two main management groups: a late planted vegetable management group and an early seeded field management group. Potato and corn stations were categorized as late vegetable plots. These plots were tilled annually and drip irrigated throughout the season. The second category encompassed the early field crops barley and brome. Field crops were not irrigated. Barley was tilled and cultivated annually, while brome, a perennial crop, was not tilled throughout the data collection period. The main reason for these crops' categorization is based on their seasonal management. Barley was planted much earlier in the spring than vegetable crops therefore defining two separate timespans for growing seasons and UDD calculation. These two categories also nicely represent two ways growers in the Interior utilize the growing season, by transplanting seedlings and planting crops with higher base temperature requirements or directly seeding into the soil once it is tillable in early spring.

Within these five cover types there were three replicates totaling 15 plots. Each plot contained a data logger and four sensors collecting hourly temperature data. Three

types of temperature data were collected at each weather station: ambient air temperature, and soil temperature at 0-5cm and 5-15cm subsurface soil depths. White radiation shields protected both the data logger and air temperature sensors from direct sunlight and precipitation at approximately standard screen height, 1.5m. The collection of data at these two soil depths independently addressed two important concepts in crop feasibility analysis: germination and root growth requirements for crops (Gliessman 2007b).

One replicate per site also measured hourly soil moisture at 15cm subsurface depth. Moisture data were collected using Decagon Devices Em50 data loggers and 5TM temperature moisture sensors at 15cm soil depth. Temperature data at these stations were collected using Decagon ECT temperature sensors. All other stations used Hobo U12-006 4-channel External data logger with four Hobo TMC-HD air and soil temperature sensors.

Weekly leaf area index (LAI) data, an estimate of the ratio between the total leaf surface area and the surface area of the ground it overlays, were collected with the AccuPAR Par80 linear PAR/LAI ceptometer of Decagon Devices. LAI measurements were acquired weekly once plant emergence had occurred. The AccuPAR Par80 has 80 photosynthetic active radiation sensors along a 1m wand. Each week three consecutive measurements were collected and averaged across all 80 sensors. These measurements produced a weekly 9 sample average for each station.

Soil texture, bulk density, total carbon and nitrogen percentages and pH were collected to demonstrate that vegetative cover and management were the only extraneous variables among the five chosen sites. Soil texture was determined using a Bouyoucos hydrometer with 50g of suspended sediment in 990mL of water and 10mL of sodium hexametaphosphate. Soil texture is one of the most stable soil characteristics and was expected to be similar throughout management types (Gliessman 2007a).

Unlike soil texture, bulk density is a dynamic characteristic of the soil that can be altered by many factors including compression, soil composition, and weather (Gliessman 2007a). Soil bulk density was calculated for every weather station at the end of the 2012 growing season.

Soil nutrients do not affect the soil temperature regime directly, but can indirectly affect them by altering the productivity of the crops that cover them. Carbon and nitrogen are major indicators of soil health (Marx et al. 1999). Composite soil samples were collected from the 0-15cm soil depth for each weather station. Two .1g samples were taken from each station to obtain an average total C and N by weight of the soil. Oven dried soil in a 1g:1mL soil/deionized water ratio was measured using an Oak Ton glass electrode pH and conductance meter.

2.3.3 Calculation Procedures

To determine the number of air and soil temperature degree-days that accrue in an Interior Alaska cultivated soil, seasonal degree-days were calculated for each weather station, depth, and for vegetation cover (crop) within both management groups. The basic calculation for degree days (Equation 2.1) is the average of daily minimum (T_{min}) and maximum (T_{max}) less a base temperature that represents the lowest temperature at which the species of interest can grow:

(2.1)

$$GDD = \frac{T_{Max} + T_{Min}}{2} - T_{Base}$$

(2.2)

$$UDD = \sum_{i=plant\ date}^{frost} \frac{(T_{Max} + T_{Min})}{2} - T_{Base}$$

Equation 2.2 displays the usable degree-day (UDD) equation which illustrates that UDDs are a summation of degree-days from the day the crop is planted to the first day of frost. For the purposes of this discussion, the base temperature used was 0°C. Daily

values are accumulated over the specified time beginning with a biofix date (planting date, emergence etc.) and ending at a specific termination point to give one unitless value: the degree-day.

2.3.4 Usable Degree-Days Concept

For seasonal calculations in this analysis, the degree-days of interest were those that are usable for the farmer in the field. That is, the degree-days that accumulated between the planting date of the crop in the field and the terminating frost. Total growing season DDs displayed in the following analyses are referred to as usable degree days (UDDs) from hereon. This view of the growing season aims to demonstrate the actual DDs available to the farmer instead of the amount that is accumulated over an entire season in the air. For some crops, harvest occurs before or after first frost, but for the purpose of this discussion, the first frost was the point considered to be the end of the growing season since little noticeable growth occurs after temperatures begin falling below freezing in the fall.

UDDs were calculated for both management groups from the observed plant date to frost. Within the early seeded/directly seeded timeframe UDD calculations were conducted for the barley, brome and bare ground plots using barley's planting date. UDDs calculated within late warm or transplanted crops were potatoes, corn and bare ground plots. Bare soil UDDs were calculated for both the early and late management

UDD timeframes in 2011 and 2012 to compare sites with vegetation to a control site without vegetation. The single presumed difference between bare ground and the vegetated sites was the vegetation itself since bare ground was rid of all vegetative growth throughout both seasons. However, one difference remained and that was that the early vegetable plots were irrigated and bare ground plots were not irrigated.

2.3.5 Crop's Effect on Soil Energy Accumulation

To determine whether or not crops affect seasonal degree-day values in the soil profile within management groups, a two-factor ANOVA was computed to test the effect of cover type and depth on UDDs for each management type and season. The TukeyHSD 95% confidence pairwise procedure was used to test statistical significance between mean UDD values to gain insight into the individual relationships between crop type and soil depth using R-statistical software.

2.3.6 Spring Lag Examination

To measure the heat energy acquired in the spring that is not usable to farmers, two analyses were utilized to document the differences between spring soil and air temperatures. The first analysis determined the thermal advantage of the air over the soil prior to soil thaw using both degree-day accumulation and calendar days (planting not available because soils are frozen). The second analysis examined the degree-day totals at the time of planting for both management scenarios (the total heat energy

acquired in the spring not available to farmers). Because data collection began at the planting date of 2011, spring lag (prior to planting date) air and soil temperature data was only available for the 2012 season.

To calculate the degree-days acquired before soil thaw, air temperature degree-days were calculated from the day average daily air temperature exceeded 0°C to the day soil 15cm deep thawed (daily average soil temperature exceeded 0°C). These calculations were done for each plot with 2012 temperature data. Because only one growing season was sampled, these calculations were also conducted using a historical 12-year air and soil temperature record from the UAF Experimental Farm (FEF) to check if the 2012 season was representative of average conditions. FEF data is collected within a quarter mile of the experimental plots presented in this research. Soil temperatures were collected daily under irrigated sod vegetation on southward-sloped terrain. When available 15 cm (6in) soil temperatures were used to determine the day soils thawed. Historical air temperature data were then used to calculate air DDs. When 15 cm data was not available, 10 cm (4in) data was used to estimate the day 15 cm soils thawed. Observing the seasons that possessed both 10 and 15 cm data supported this assumption because the lag between thaw at the two depths was slight and on average one to two calendar days apart.

To quantify the heat energy acquired in the spring that is not used by farmers, total spring degree-days were accumulated between the day each depth's daily degree-

day value became positive to the day of planting for each plot. This same calculation was conducted for air temperature values and compared to each depth to provide more context of the lag in heat energy within the soil in the spring. A t-test was performed at a 0.05 significance level to determine if there was a difference between air temperature DDs and soil DDs before planting date.

Unlike total season UDD calculations, the majority of crops across both management scenarios were used in comparison to one another because the two differences between plots: vegetation and management differences (irrigation and planting dates) are not present in the spring. This lack of vegetation allowed for the assumption of equality within physical and environmental factors among plots. For field spring degree-days all five crops are compared to one another. One exception was made for late vegetable spring DDs because growth had begun in brome fields before the vegetable planting date occurred and was therefore not used as a comparison with the vegetable crops.

To demonstrate how the UDD values of both the soil and air temperatures compare on a seasonal level, the total seasonal UDDs in the soil for each crop was then compared to the average temperature UDD value for the 2012 season.

2.4 Results

2.4.1 Soil Characteristics

All sites have a soil textural class of silt loam (Table 2.1). A neutral pH value was reported for every cover type (Table 2.1). Bulk density results are presented in Table 2.2. Bare ground experienced a mixed tillage regime during the observation period; bare ground was tilled the first season but left untilled the second season, exhibiting a final bulk density value of 0.87 g/cm^3 (Table 2.2). Barley, corn and potato plots were tilled annually each spring. Brome and bare sites were not tilled annually potentially accounting for the slight difference in bulk density values between the sites (Table 2.2). Although sample size was small and no statistical analysis performed, both brome and bare soil bulk densities were higher than other tilled crops with a brome crop average of 0.83 g/cm^3 while corn, potato and barley were less dense with respective bulk density values of 0.65, 0.65 and 0.74 g/cm^3 (Table 2.2). Total nitrogen and carbon were non-limiting and results are presented in Table 2.3.

2.4.2 Soil Moisture

Hourly moisture data in the form of volumetric water content or ratio of the volume of water to volume of soil (m^3/m^3 VWC), collected at 15cm depth for each crop type is presented in Figure 2.1. Moisture data demonstrated an important difference among the two management systems sampled in this study: corn and potato crops were

drip irrigated where field crops, including bare ground, were non-irrigated. Permanent wilting point for a silt clay loam is about 10-15% VWC (Hanson et al. 2000; NRCCA 2010). Average silt loam soil saturation point is about 0.30 for field capacity and 0.15 for a wilting point (Hanson et al. 2000). In general, irrigated crops remained above the range of permanent wilting point for a silt loam soil with the exception of corn in 2012 dipping within the 10-15% range near the end of the season. Non-irrigated crops remained less moist than irrigated crops for the majority of both growing seasons with the exception of corn in 2012.

Dramatic increases in soil moisture content present throughout all five sites correlated with multiple day (>2) rain events. The largest spike in the data corresponds with the week of snow melt and soil thaw in April of 2012. This increase in soil moisture happens just about as quickly as it disappears suggesting that a large amount of infiltration to lower depths occurs as the soil thaws and evaporation occurs at the surface removing much of the moisture accumulated over the winter from the top 15cm of the soil column.

In 2011, the irrigated crops fairly consistently maintained more soil moisture compared to non-irrigated crops. Soil under the corn consistently reported the highest moisture levels out of all crops and soil under the brome the lowest. As the representative of a closed canopy crop, corn shaded the soil surface more than the potato crop, likely reducing evaporation from the soil surface. This ability to produce the

most biomass with little evaporation from the soil surface coupled with low transpiration levels is referred to as T efficiency (Gliessman 2007a). Out of the crops sampled in this study, corn is thought to be the most T-efficient crop followed by barley and then potatoes (Lyon et al. 1952; Gliessman 2007a) providing reason for its consistently higher values of soil moisture. It is not exactly clear where brome grass would rank among these crops in terms of T efficiency. It is conceivable that brome would be close to barley due to its similar physical structure but with the lack of annual tillage, there are complexities due to brome's different surface conditions including weeds, stubble, and resident organic matter that can all affect soil moisture (Gliessman 2007a). It is assumed that a detectable portion of the rain brome receives does not necessarily reach the soil column as moisture is held in the organic matter at the surface. However, the surface of the mineral soil is buffered from direct sunlight, potentially reducing evaporation (Gliessman 2007a). It is important to note, however, that the two irrigated crops, were not always irrigated identically; likely adding to the variability between the irrigated crops.

In 2012 potato soils consistently reported the most moisture content throughout the growing season while brome remained consistently the lowest ranking crop. It is important to note that corn and barley sensors were moved during planting in 2012 due to field management needs. There was an observed drop in corn soil moisture content directly after the sensor was moved. This shift in moisture content directly after sensor

movement seemed to continue producing lower values throughout the rest of the season as it was no longer the highest-ranking soil moisture crop. It is unclear why corn reported lower values throughout the 2012 season when compared to its ranking among sites in 2011. Having only one data point for each crop makes it difficult to determine what could have ultimately affected these values. When sensors were moved, conditions were controlled to produce constant variables as much as was possible but there are inevitable differences even within the same field and management system.

Once soils freeze, moisture is presumed to be negligible, however, collected data report a detectable amount of moisture. Reported soil moisture throughout winter is due to the combined effect of slight moisture content in frozen soil (Kane and Chacho 1990) and dielectric permittivity of ice (Personal Comm., Decagon Support April 9, 2013).

These observations suggest that the non-irrigated soil moisture content values were more susceptible to the dynamics of the weather and vegetation throughout the season. In both 2011 and 2012, barley and brome decrease moisture values outside of rain events as crops grow and transpire while bare ground remains relatively stable. Corn and potato crops in the irrigated field maintain relatively stable moisture levels, gradually decreasing throughout the 2011 season. The 2012 season appears to be more

dynamic for irrigated crops than the 2011 season with the movement of the corn sensors and the relatively large rain events.

2.4.3 Seasonal Usable Degree-Days

Results of the total accrued seasonal usable degree-days (UDDs) are presented in Figure 2.2. The highest average UDD value was recorded at the 5cm depth under bare ground cover. This observation was consistent between the two seasons. Lowest average UDD values were recorded at the 15cm depths. Field crop temporal calculation boundaries were longer than vegetable crops and higher in both seasons at all depths.

Early field crop UDD calculation boundaries were May 17 through September 25 in 2011 and May 16 through September 8 in 2012. Late vegetable planting and frost date boundaries for UDD accumulation were June 6 and Sept 25 in 2011 and June 1 and Sept 8 in 2012. Average UDD values were calculated for each crop using daily data from three weather stations within each crop management type (n=3).

Air temperature UDDs from all 15 stations accrued within the late vegetable crop timeframe were 1600 and 1550 for the 2011 and 2012 seasons respectively. Field crop air temperature average for 2011 and 2012 season was 1950 and 1930 respectively.

Bare ground 5cm soil UDDs calculated within the late vegetable time span were 1760 and 1680 in 2011 and 2012 respectively. Bare ground 15cm soil UDDs were 1680 and 1630 in 2011 and 2012 respectively (Figure 2.2). Bare ground UDDs for the early

field crop calculation period was on average 2100 at 5cm and 1960 at 15cm in 2011. In 2012, average field UDDs for bare ground was 2040 at 5cm and 1910 at 15cm (Figure 2.2).

In 2011 the three-station average for corn soil UDDs at 5cm was 1660 ranging from 1570 to 1610. In 2012, corn 5cm soil UDD value was 1530. Similar corn early maturing corn varieties were planted for both the 2011 and 2012 seasons. Both years, the corn station LAI average peaked at about 2.5 LAI although 2012 season peaked earlier than 2011 (Figure 2.3). Throughout the 2011 growing season, corn reached the R1-R2 growth stage meaning kernels did not reach full development. Plant structure reached full potential but grains did not fully mature. This measurement was replicated in 2012 as corn development again reached about R1-R3 growth stage and kernel development did not reach full maturity.

Average potato 5cm soil UDD values were 1660 and 1690 in 2011 and 2012 respectively (Figure 2.2). In both the 2011 and 2012 seasons, potato plants reached full maturity and potatoes were harvested after the first frost. Varieties were similar in structure and not expected to cause differences in soil temperatures due to canopy structure.

Average potato LAI for the 2011 season was about 3.3 whereas LAI peak in 2012 was about 1.4 (Figure 2.3). The exact reason for the increased variability among sites in

2012 is unknown, however observations of the stations' characteristics lead to a couple possible explanations. In 2011 one station became completely covered by an individual plant that grew sideways. In 2012, potato station 3's neighboring plants were stunted presumably due to disease or herbicide contamination. This station exhibited the medium 5cm UDD value but the highest overall 15cm UDD value within the potato stations. Stunted growth surrounding a potato plot's sensor resulted in a vegetation cover that closely resembled bare ground, theoretically decreasing the insulative effects of vegetation cover and increasing soil UDD values throughout the season.

Brome soil UDDs for 5cm depth was 1940 and 1870 in 2011 and 2012 respectively. UDDs for 5cm ranged 1910-1980 in 2011 and 1840-1900 in 2012. Brome 15cm soil UDDs for 2011 and 2012 were 1810 and 1760. The range for 15cm UDDs was 1720-1860 in 2011 and 1660-1880 in 2012 (Figure 2.2). Between the two seasons brome 15cm variability was highest for the early field management scenario.

Barley soil UDDs at 5cm were 1940 and 1960 for the 2011 and 2012 seasons respectively. 15cm UDDs for the 2011 and 2012 seasons were 1830 and 1820. For both seasons, there were three varieties of barley planted among the three stations that may have produced slight variations in temperatures at the soil surface. LAI values display that the overall cover of each variety peaked simultaneously for both the 2011 and 2012 season (Figure 2.2).

2.4.4 Crop's Effect on Soil Energy Accumulation

A two factor ANOVA allowed for multiple ways of examining how cover type affects UDDs at varying depths within the soil profile (Figure 2.2). Within both the 2011 and 2012 growing seasons and both management scenarios it was determined that depth, cover and the combined effect of depth and cover were significant factors in determining UDD values.

When selecting the effect of both depth and cover within each management scenario and season, it was determined that no difference existed among air temperature values but mixed results were measured for the individual crop's effect on soil temperature values. In 2011, there were no differences detected between crops in both management groups at both the 5 and 15cm depth. All crops were different from bare ground UDD totals at both the 5 and 15cm depths (Figure 2.2).

In 2012, results presented a mixed picture of crop's effect on soil UDDs. Brome was consistently different from bare ground at both 5 and 15cm depths but changes in results were measured in potato, corn and barley. In 2012, both barley and potato were not different from bare ground at both the 5 and 15cm depth. Potato plots were not different from bare ground at any depth. However, the only depth and season where a difference was detected between crops within either management group was between corn and potato covers in 2012 at the 5cm depth.

When considering cover type as the only factor of importance across all depths, there was no difference between brome and barley but both brome and barley were different from bare ground. In 2012, there was a marginally significant ($P=.03$) difference between brome and barley (Figure 2.2). When only considering crop type as the factor of importance for the late vegetable scenario, there was no difference between potato and corn in 2011 but a difference detected in 2012. In 2012, potato plots were not different from bare ground plots (Figure 2.2).

When only considering the effect of depth on UDD values across early season field crops, there was a significant difference between the 5cm and 15cm, air and 15cm, but not between 5cm and air for both the 2011 and 2012 seasons. For late vegetable scenario in 2011, there was a difference between 5cm and air, as well as 5 and 15cm but not between 15cm and air (Figure 2.2). In 2012 the only significant difference among depths was between air and 5cm.

2.4.5 Spring Lag

Air temperature DDs were calculated to quantify the number of air temperature DDs that accrue before soils thaw in the spring to demonstrate the initial thermal advantage of the air over frozen soils. For the 2012 growing season, a 15 site average of 90 degree days was recorded to accrue in air temperature DDs before 15cm depth began accumulating DDs (exceeded 0°C). The range among the 15 sites was 73-105DDs

and the standard error was 2 (Table 2.4). The number of calendar days observed between these thresholds ranged from 20-22 days.

These same DD calculations prior to soil thaw were also calculated using a historical FEF 12-season dataset. This exercise calculated an average of 103 air DDs before the daily 15cm soil temperatures exceeded 0°C and therefore began DD accumulation (Table 2.5). The range of this data was 63-240DDs with a standard error of 14. The average number of calendar days was 27days. The value acquired from the 2012 season data collected for this research was 91DDs and fits within this 12 season range. In 2009, the air DD value was 240 which was over three inter quartile ranges from the 3rd quartile of the data leading to the conclusion that this value was an outlier of the dataset. It is not clear what caused this value but this year also exhibited the warmest January high on record (ACRC, 2013) and the snowpack was affected slightly (decreased 5cm) around the time of the temperature high. Although the snowpack was not lost completely this loss in snow is a possible explanation for the observation of the coldest March soil temperatures over the 12 years of available data due to the loss of insulation during the coldest period of the year. Excluding this value as an outlier, the average of the now 11-year dataset is 90Ds with a standard error of 6DDs. This value is only one DD different from the spring DD value collected in 2012 from the 15 weather station averages.

Spring DDs (0°C through planting date for each depth) is another way this research examined the discrepancy between air and soil heat energy accumulation. Figure 2.4 displays the crop mean and standard error (n=3) of total spring DDs before planting date for both late vegetable and early field crops for all depths. Air temperature degree-days began accruing on March 28 and the plant date for field crops was 5/16 and 6/1 for vegetables in 2012. This total value displays the potential error in calculating DDs for farmers using only calendar days or seasonal boundaries based solely on air temperature exceeding 0°C. When these unusable DDs were included in the UDD calculation, there was a 13.3 and 30.7% increase in UDDs for early field and late vegetable crops respectively.

To understand the significance of the discrepancy between the heat energy acquired by the air compared to the soil, T-tests were performed that examined the difference between air and soil spring DD values (0°C through planting date). For early field crop management scenario, the discrepancy between air temperature DDs and soil DDs were different ($P=.05$) at both 15 and 5cm depths. The vegetable planting date DDs resulted in no difference for Barley at 15cm, but marginal significance ($P=.03$) for potato 5cm indicating that bare and corn 5cm values were different. All vegetable crop values were different at the 5cm depth.

Figure 2.5 displays daily average temperatures for air, 5cm and 15cm soil depths. Daily minimum air temperature is also included to investigate its relationship to planting

date. Soil temperatures slowly begin to increase before snow has completely melted, but once snow melt occurs, soil temperatures (0-15cm) quickly pass the 0°C isotherm. Soil thaw appears to be highly correlated with snowmelt. There were 9 calendar days where the average air temperature is above 0°C, but the insulative qualities of the snow buffer the soil from change until snow melts and soils thaw. Once soils have thawed, soil temperatures quickly climb to match a dampened version of air temperature for the rest of the season.

Soil temperatures at 15cm lagged behind 5cm temperatures; thawing two days later than 5cm (Figure 2.5). Over the growing season, 15cm daily average temperatures are colder than 5cm except in periods of cooling throughout the season. Daily average 15cm soil temperature surpassed 10°C within three days of air temperature averages, demonstrating that perhaps soil temperature is not the only limiting factor in determining planting date.

2.5 Discussion

2.5.1 Factors Affecting Plant Dates

Results suggest that there are a considerable amount of air temperature degree-days that accrue before planting can occur in Interior Alaska agriculture fields. Although a lag in soil temperatures and air temperatures was measured, it is not clear to what extent this lag in soil temperature alone is the sole hindrance on planting dates and therefore growing season lengths. Observations and measurements of planting dates,

soil and air temperature, snow melt and soil moisture provided a glimpse of the biophysical boundaries inhibiting agriculturalists indicating that the notion that the soil's temperatures alone limit the spring portion of the growing season for agriculturalists may be too simple of an interpretation of the Interior spring planting thresholds.

Numerous discussion points are demonstrated in Figure 2.5 including snow melt and soil temperature relationships, planting date estimations and the importance of daily minimum air temperatures. Figure 2.5 demonstrates that while soil temperature is an important factor for growth and germination, daily minimum air temperature is also of paramount consideration in terms of determining planting date. Daily minimum temperatures are especially important to crops that are transplanted to the field as seedlings.

The beginning of soil temperature DD accumulation was correlated to the week that snow cover was observed to melt. Snow is known to be an insulative layer from cold temperatures in the winter but also keeps them cool until it melts and the soil is exposed to the more dynamic air temperatures. Farmers and gardeners alike account for this by instigating practices, such as spreading ash on snow, to speed up the melting process. This result suggests that determining snowmelt could help hone the isolation of variables that determine when farmers are able to plant.

Typically, average daily soil temperatures are cooler than air temperatures in the spring. This lag in temperature alone is likely not the only factor inhibiting planting

dates. For example, 5 cm soil exceeded the daily average 10°C threshold within one day of air temperature and 15 cm within 3 days (Figure 2.5). Because 10°C is noted as a one of the highest base temperatures needed in the soil required for growth and development for warm marginally successful crops such as corn (ACE 2013), the assumption would be that planting could occur on this date. However, planting did not occur until 14 days later, once nightly temperatures were no longer lower than 4°C and 15cm soil daily average temperature and minimum was around 12°C. Daily soil temperature minimum for 15cm had been at least 10°C for 10 days.

This suggests that once the soil has thawed the determination of planting feasibility is much more complex than the soils being cool in the spring. Observing the air temperature minimum suggests that soil temperatures were not the only limiting factor for transplanting or planting crops that need warm soils and warm daily minimum temperatures. Transplanted crops require higher air temperature minimums and roots can be negatively affected if shocked by cool soil or air temperatures.

Results demonstrate planting dates for the early seeded crop (barley) was less constrained by daily minimum temperatures dipping below zero than the late crops and appeared to correlate more with the base temperature requirements in the soil. Barley was planted two days before the air temperature minimums ceased dropping below 0°C for the season. Soil temperature average was 7°C at 5cm (estimated seed depth) with a daily minimum of 5°C. This timing works well for crops like barley that have low base

temperature requirements because cool temperatures immediately after planting do not hinder success. If however, the temperatures would have dropped back below freezing and resulted in a hard frost after emergence, the crop would be affected. For farmers, determining this point at which temperatures will be consistently above zero is a delicate balance between maximizing the growing season and putting a crop at risk. For example planting barley, as late as the middle of May can cause a delay in maturation, lower yields and even reduced quality (Wooding and Knight 1973; Van Veldhuizen and Knight 2004) whereas planting too early could also result in the loss of the crop if extreme enough freezing occurred; leaving a potentially very short growing season.

Soil moisture can be a limiting factor in terms of planting dates. Directly after snow melt, the soils are saturated and cannot be prepared for planting. At FEF from 2005 to 2012, observed snow melt to planting date for directly seeded grains ranged from 14-27 days. Once the soils are dry enough to till, FEF managers are tilling the soil and getting the fields ready to plant as soon as possible (Personal Comm., Seefeldt November 20, 2012). Knowing this, it is possible that for low base temperature crops, that soil moisture is more limiting in the spring than actual soil temperatures. This is likely due to the fact that at FEF, the fields are not irrigated and the soil moisture gained in the spring due to snowmelt is necessary for successful germination (Van Veldhuizen and Knight 2004).

This lag between air temperatures exceeding 0°C and planting date in the spring appears to depend on a complex interaction between soil temperature, soil moisture, and air temperature minimums. However, it is inherent that planting dates are affected by many variables outside of biophysical requirements. Each farm has a different management system in place that must react based on factors that are out of the realm of simple biophysical characteristics of the land including cultural influences (Van Veldhuizen and Knight 2004) perception of risk, financial constraints, goals, labor availability, and reliability of or access to needed infrastructure and equipment.

FEF is a research facility that does not define management practices for the purpose of profit, but for the priority of research. This could introduce bias into the selection of a planting date when compared to other farms in the Interior due to a unique perception of risk in losing a crop, for example. It has been noted that FEF plant dates are in line with other local planting dates, with perhaps a slight bias towards being more proactive based on biophysical characteristics alone (Steven Seefeldt Personal Comm., November 20, 2012). However the general rule of thumb for planting in the Interior is that it is generally safe to plant all vegetable crops by the first week of June. The planting dates observed in this research for vegetable crops were planted in that week leading to the assumption that the FEF planting date was in line with most growing locations in Interior Alaska.

Furthermore, it should be noted that planting dates are generally estimates of the actual day crops are planted. Planting in the vegetable plots of FEF had begun as early as 5 days prior to the planting date of corn and potato due to resource limitations. Conditions for the previous week were similar enough to the actual planting date that planting had begun in other sections of the field days prior to the actual plant date for corn. This demonstrates the potential subjectivity of observed planting date as a measurement.

There is potential for error when comparing two different datasets to one another. Differences were observed when the 15 plot datasets collected for this research were compared to the FEF weather station historical data. Although the DDs calculated prior to soil thaw produced in this research was in line with FEF past seasonal trends, the 2012 season from the FEF data produced an average air DD of 66 compared to the 91 DDs collected for this research (Table 2.5). However, the 15 site values ranged from 73 to 105 DDs. FEF data are collected under irrigated sod vegetation on a South facing aspect about 10 m higher than the 15 stations on that were on level ground under the 5 crop type covers. Differences between sites including slope, aspect, vegetation, runoff and compaction are the main assumptions for these differences in accumulated values between data collection sites.

2.5.2 Spring Data Collection Considerations

Although there were significant discrepancies between soil and air temperature degree-days at both the 5 and 15cm depths at the time of planting date for both management groups (early and late), the difference between accumulated soil and air heat energy was observed to dissipate as the season continued. Figure 2.4 demonstrates that although there is a thermal advantage of the air over soil in terms of DDs in the spring (Swanson et al. 2000), throughout the season soil DDs generally equal or surpass air temperature DDs at 5cm depths. As DDs are the average of the daily maximum and minimum temperatures it is logical that soil being less dynamic, or less susceptible to short term temperature fluctuations, would therefore steadily accrue degree-days throughout the season whereas air temperature degree-days may be more sensitive to temperature extremes.

In order to draw comparisons among crop types for spring soil energy accumulation examinations, it was assumed that spring soil surface conditions were comparable. Spring soil surface conditions were not identical among all plots, however the differences were considered to be negligible until new growth emerged. Brome is a perennial crop with leaf litter and roots left throughout multiple seasons making the surface conditions different from other crops in the spring and throughout the season.

Barley had minimal crop residuals and about 15cm stubble left until tilling was feasible. Corn and potato crops have minimal crop residuals left on the surface throughout the spring. In comparing spring DD totals among all crop types (Figure 2.4), brome crops were not treated identically between analyses for the two management systems. All crops were compared to one another for the field management scenario whereas for the late vegetable crops, brome plots were not used because brome crop had already begun to grow at the time of potato and corn planting date.

Barley crops soil was tilled earlier than the potato and corn plots in the 2012 spring potentially explaining the slightly higher spring DD accumulation by the late management planting date. Figure 2.4 demonstrates that barley crop spring DDs were not different ($P=.05$) from air temperature DDs where bare ground, corn, and potato were different at both the 5 and 15cm depths. By the time the late crops were planted, barley was tilled and cultivated earlier. This earlier mixing of the soil surface layers is considered to be an explanatory variable for the increased values seen at both barley depths versus other late vegetable DD calculations as aeration and warming in the soil due to tillage had already occurred (Gliessman 2007a).

Another data collection consideration is the fact that both barley and corn plots had to be removed and replaced directly prior to planting in 2012 due to field management requirements. This change, although slight (within 30cm for corn and 3m for barley), the relocation of data collectors introduces errors in comparing values

between years. This analysis, however, does not focus on comparing the two years to one another but examines how crops affect the UDDs and how spring temperatures affect plant date determination.

2.5.3 Crop's Effect on UDD Accumulation

Confidence in the assumption that within each management group there is only one variable separating plots (crop type) was supported by the lack of differences in air temperature UDDs among crop types in tandem with similarities in basic soil properties. It was hypothesized that soil UDD values would differ among cover types but that no difference should be detected among air temperature UDDs. The differences between air temperatures among the sites were hypothesized to be insignificant because they aimed to sample similar air temperatures above differing canopies. The null hypothesis for air temperature UDD values was that within each management category and season, differences between crop air UDDs would be zero. The null hypothesis was supported with 0.95 confidence that no difference existed between sites within each season or management category. This conclusion provided confidence that the differences seen within the soil column could mainly be attributed to vegetation type and assumed moisture differences.

There were two ways in which differences between crops were analyzed. When only the factor of cover type was analyzed, barley and brome were marginally different

in 2012. Although there was a larger difference between the total UDD values in 2012 than there were in 2011, when observing the interaction factor of depth and cover type, barley and brome were not different at both the 5 and 15cm depths in both 2011 and 2012 (Figure 2.2). Potato and corn were different from one another for both analyses but only for the 5cm depth in 2012 when considering the interaction variable.

Aside from this one exception in 2012, there was a lack of consistent difference between crops within similar management categories at either depth when the combined effects of both depth and cover type were recognized (Figure 2.2). This result suggests that the type of vegetation within a management strategy does not always affect mean seasonal degree-day values consistently throughout the soil column from 5 to 15cm. This is especially true for the 15cm depth no differences were measured among crops for the two seasons for either management strategy. Furthermore, the crops selected were intended to represent a wide range of crop structures that would be implemented in an Interior farm. Marginal differences suggest that the majority of crops with more similar structures to either closed (corn) or open (potato) canopy crops would likely not affect soil temperatures significantly enough to require reclassification.

For field crops, this suggests that in terms of seasonal averages between planting date and frost, there was little to no difference between crop types. This can be extrapolated further and suggest that tilled and non-tilled crops are competitive in terms of heat energy accumulation throughout the growing season.

In both management groups in 2012, there were instances of a crop resembling bare ground. This is not an unexpected result because agricultural vegetation is not expected to be as effective in influencing soil temperatures as a forested plot would be (Grunzweig et al. 2003). When comparing bare ground UDDs to vegetated soils within management types, results were mixed. For example in 2012, no difference was found between bare ground and barley or potato crops at any depth (Figure 2.2). This is not an unexpected result for potato plots as they closely resemble bare ground for a considerable period of time in the spring. In the 2012 season, potato emergence occurred 3 weeks later than any other crop.

Due to the potato plot's intended representation of open canopy crops (each plot within 1m of three individual plants), soil temperatures at any given location were expected to be more sensitive to changes in individual plant developments. Potato plant proximity to sensors was consistent among the three stations to reduce potential inconsistencies among stations, however individual plant responses to environment, disease and herbicide contamination could not be controlled and were considered relevant representation of the randomness likely experienced in farms across The Interior.

Mixed results indicated that in general, agricultural vegetation affects the number of soil UDDs, but that the type of agricultural vegetation does not always mean

it will significantly different than if the ground was left fallow and removed of vegetation.

A lack of difference between air and soil UDDs can have important implications for future projected air temperature models in determining soil temperature accumulation in future decades. Within the early field crop management strategy, air UDDs were not different from 5cm UDDs overall. Because of this lack of overall difference between the two “depths” it can be assumed that projected air temperatures may produce a reasonable estimate for 5cm UDD values. Similarly for the vegetable management strategy, air temperature was a good estimate for 15cm UDDs because of a lack of overall difference between the two “depths”. This indicates that a projected air UDD estimate would likely be a reasonable estimate of 15cm UDDs. This also suggests that a generalization among different management groups (early field or late vegetable) scenarios for the future should be relevant for agricultural scenarios to the end of the century.

2.6 Conclusions

The premise of this research was that spring air temperature degree-days (DDs) begin accruing much sooner than soil temperatures in the Interior Alaska. This discrepancy can give false pretenses about what can actually be grown in Interior Alaska when estimates are only dependent on air temperatures DDs that do not take into

account non-usable spring degree-days. This research attempts to dissect the difference between soil and air temperature degree-days in the spring to examine how spring soil temperatures limit agricultural production in Interior Alaska. Including non-usable spring degree-days in UDD totals resulted in a 13.4 and 30.7% increase in usable degree-days for early field crop and late vegetable crop scenarios respectively. Within crop management scenarios, no difference was measured among crops in terms of affecting UDDs in 2011 but inconsistent results were found at the 5cm depth in 2012.

A lag between soil and air temperatures in the spring exists in Interior Alaska, however soil temperatures alone do not appear to be the sole limiting factor for farmers to determine planting date. The lag between air temperature and soil thaw was 91DDs for 15 sites in 2012. Once snow was removed and average daily air temperature was consistently above 0°C, soils thawed and warmed up to match the seasonally observed pattern air temperatures dampened by depth within a matter of about 10 days. Even once soil temperatures caught up to air temperature, minimum air temperatures did not cease dropping below zero until about 5 weeks later. Once soils were thawed and tilled, the top 15cm of soil heats up quickly increasing the likelihood that air temperature minimums are more important in determining planting date than soil temperatures, especially for fragile transplanted crops.

As topography, soil composition and aspect are known to affect air and soil temperature, further research and extensive data collection should address the effects

of these incongruities on soil temperatures and growing season lengths of Interior Alaska farms to further downscale the precision of this research to match all farming conditions. These measurements, however, provide the preliminary data necessary to begin discussions around farmer usable degree-days for different land management regimes under future climate scenarios.

2.7 Figures

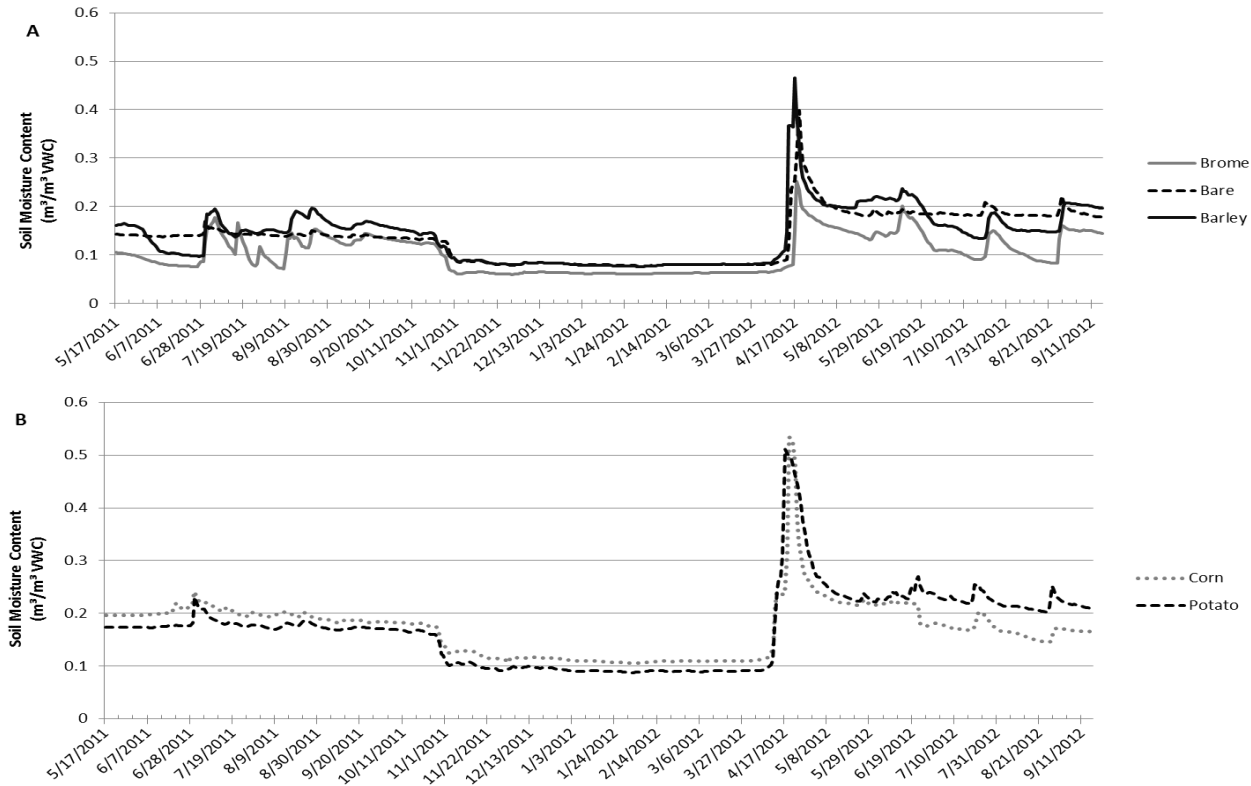


Figure 2.1 Daily mean volumetric soil water content (m³/m³ VWC) from 15cm soil depth. The five crop types are split into two separate categories based whether or not the field was irrigated: A) non-irrigated and B) drip-irrigated. Data range from barley planting date in 2011 to harvest in 2012.

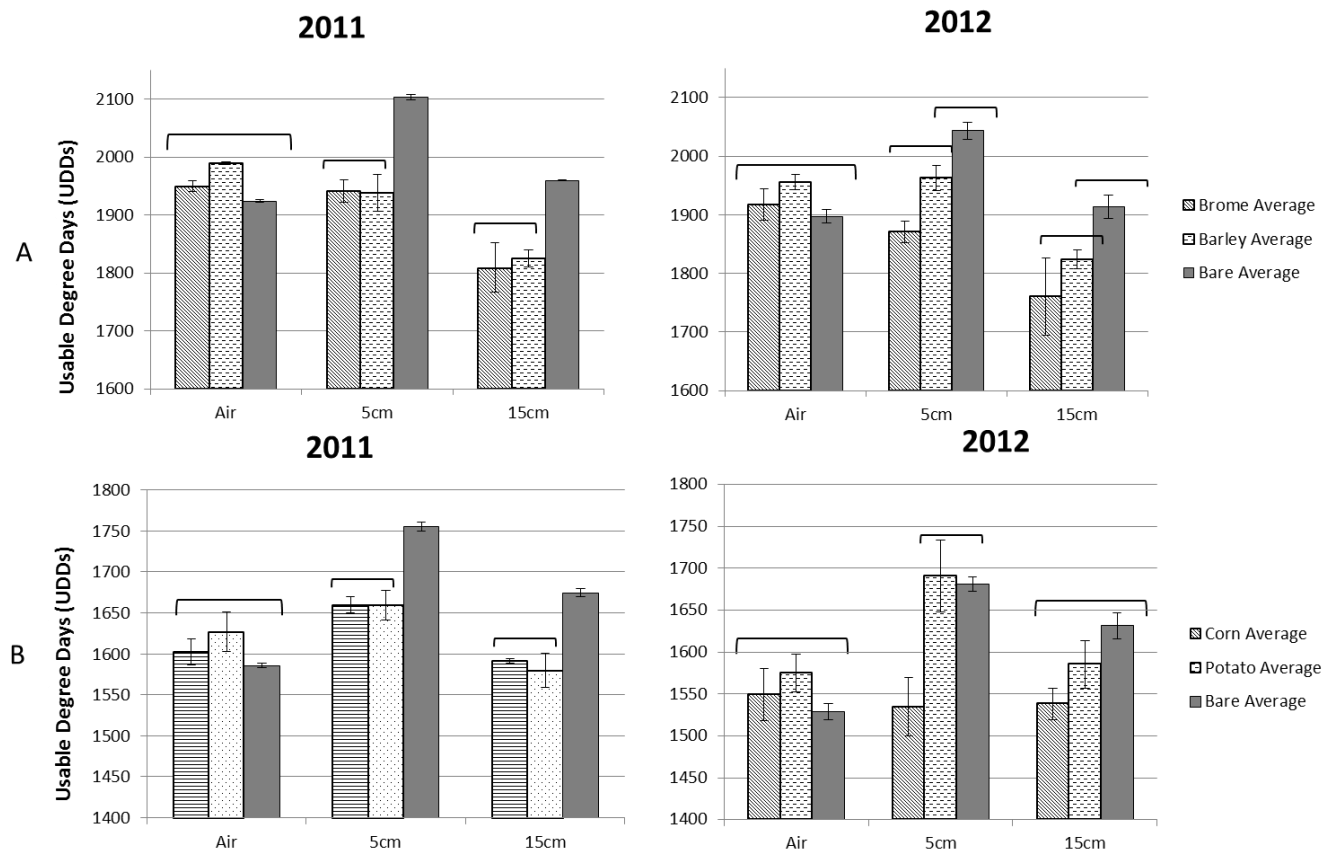


Figure 2.2 Mean usable degree-day (UDD) values for the 2011 and 2012 season for each sampled crop within the A) field and B) vegetable crop category (mean \pm one standard error; $n=3$). Values are expressed in UDDs with a base temperature of 0°C. Brackets indicate statistical insignificance among vegetative cover within each depth based on two factor ANOVA analysis results.

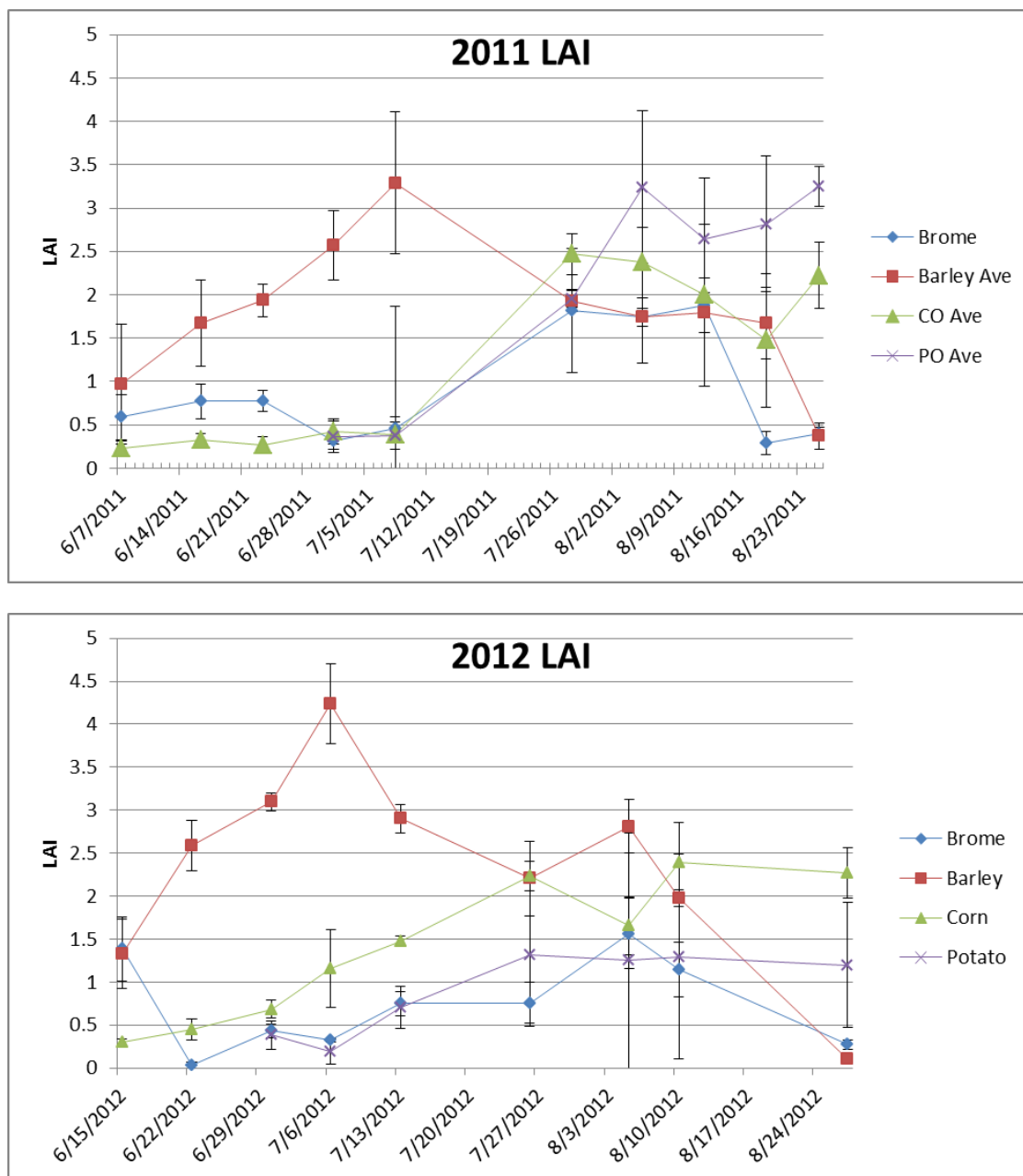


Figure 2.3 Weekly mean leaf area index (LAI) values for 2011 and 2012 seasons (mean \pm 1 standard error, n=3).

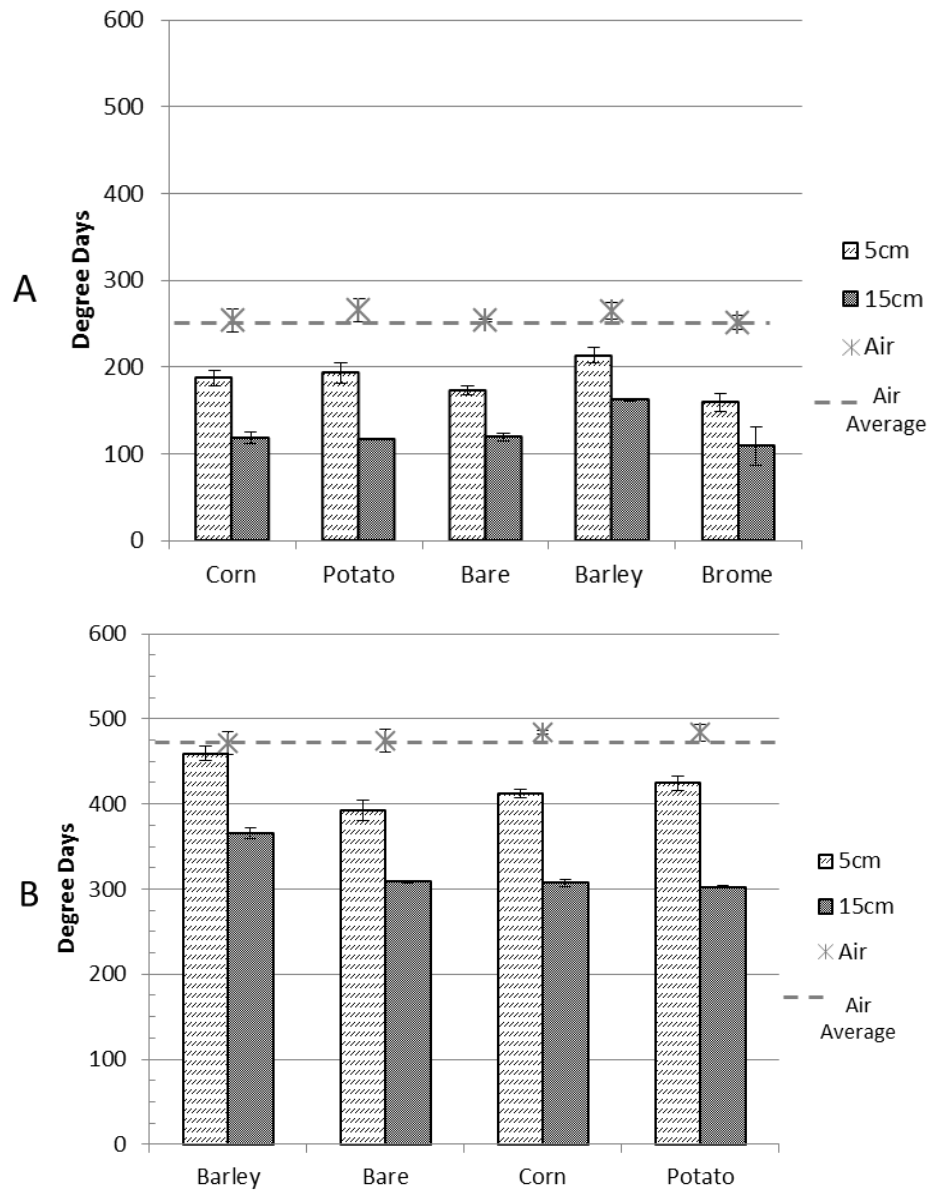


Figure 2.4 Spring degree-days (DDs) (mean \pm one standard error, $n=3$) from the first day of positive daily DD values to planting date in 2012. DDs were accumulated between March 28 and May 16 for early field crops and March 28 and June 1 for late vegetable crops. Points represent the three station average for air temperature from each crop type. The dotted line is the average accumulated air temperature DDs for all stations ($n=15$). Field air temperature value was 258 with a standard error of 9 and the vegetable average air DD value was 476 with a standard error of 12 ($n=3$).

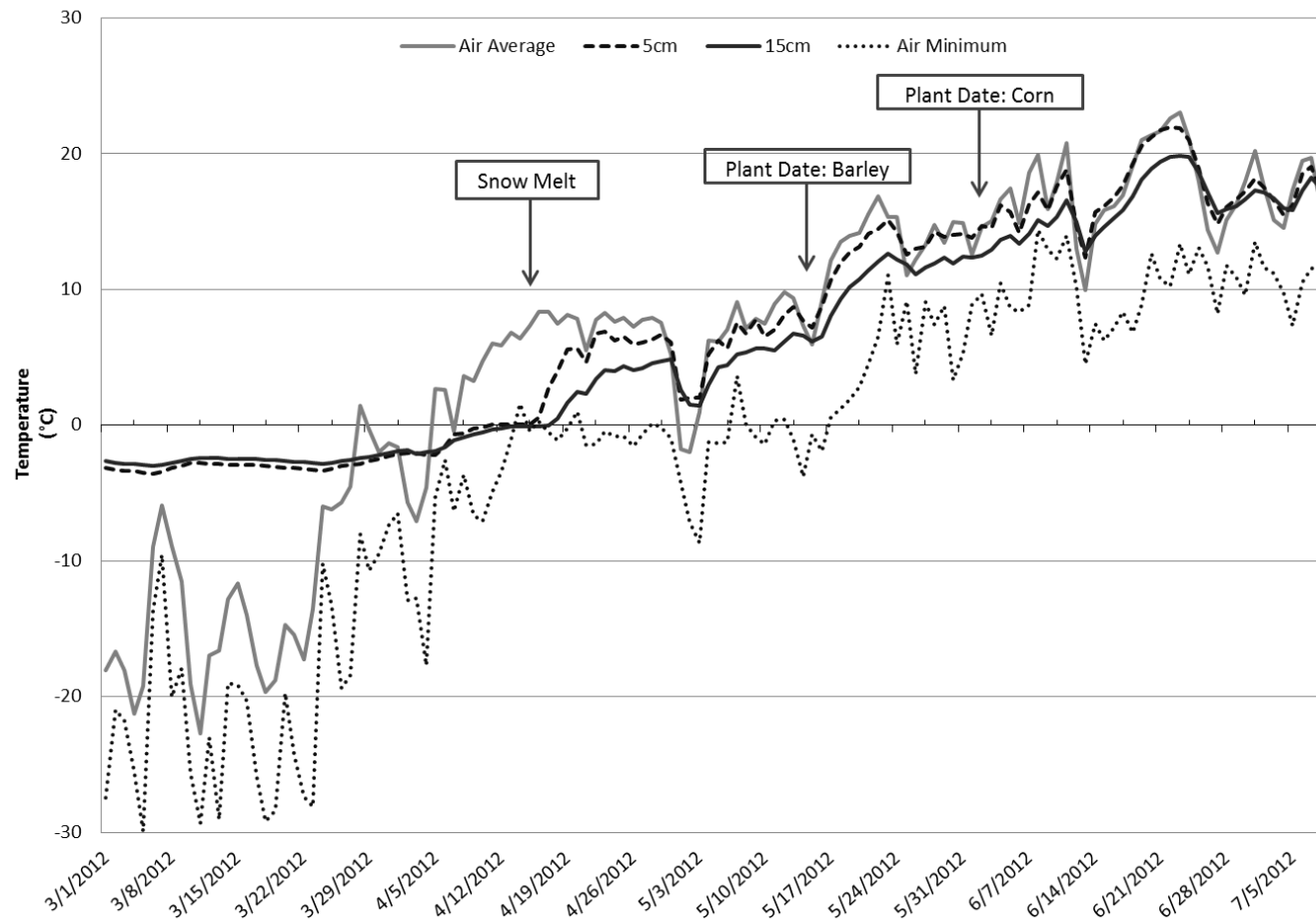


Figure 2.5 Daily average air, 5cm and 15cm temperatures for spring of 2012 compared to daily air temperature minimum. Corn temperature data is presented here (n=3). Observed estimates of snow melt and planting dates are indicated for both corn and barley.

2.8 Tables

Table 2.1 Percent clay, sand, and silt and pH determining soil texture and acidity for all plots.

| | % Clay | % Sand | % Silt | pH |
|--------|--------|--------|--------|------|
| Corn | 12 | 20 | 68 | 6.62 |
| Potato | 11 | 22 | 67 | 6.70 |
| Bare | 12 | 16 | 72 | 6.91 |
| Barley | 16 | 14 | 70 | 6.86 |
| Brome | 13 | 17 | 70 | 6.60 |

Table 2.2 Single sample soil bulk density (g/cm^3) for each of the 15 temperature stations.

| Site | Bulk Density g/cm^3 |
|---------|--|
| Brome1 | 0.85 |
| Brome2 | 0.82 |
| Brome3 | 0.83 |
| Bare1 | 0.81 |
| Bare2 | 0.92 |
| Bare3 | 0.87 |
| Barley1 | 0.75 |
| Barley2 | 0.71 |
| Barley3 | 0.77 |
| Corn1 | 0.70 |
| Corn2 | 0.64 |
| Corn3 | 0.60 |
| Potato1 | 0.67 |
| Potato2 | 0.62 |
| Potato3 | 0.65 |

Table 2.3 Two sample average total Carbon and Nitrogen (wt%) for each of the 15 temperature stations.

| Sample | N (wt%) | C (wt%) |
|----------|---------|---------|
| Brome1 | 0.255 | 2.938 |
| Brome2 | 0.308 | 3.804 |
| Brome3 | 0.296 | 3.777 |
| Bare1 | 0.301 | 3.543 |
| Bare2 | 0.307 | 3.583 |
| Bare3 | 0.324 | 3.896 |
| Barley1 | 0.246 | 2.877 |
| Barley2 | 0.272 | 3.150 |
| Barley3 | 0.258 | 3.090 |
| Potato 1 | 0.387 | 4.424 |
| Potato 2 | 0.429 | 4.799 |
| Potato 3 | 0.421 | 5.014 |
| Corn 1 | 0.381 | 4.215 |
| Corn 2 | 0.379 | 4.042 |
| Corn 3 | 0.397 | 4.247 |

Table 2.4 Accumulated spring air temperature degree-days prior to 15cm soil thaw (daily average degree-day exceeded 0°C).

| | Plot 1 | Plot 2 | Plot 3 |
|----------|----------------|--------|--------|
| Potato | 82 | 105 | 91 |
| Corn | 93 | 92 | 74 |
| Brome | 95 | 97 | 99 |
| Barley | 73 | 84 | 88 |
| Bare | 88 | 100 | 100 |
| | | | |
| Average: | Standard Error | Min | Max |
| 91 | 2 | 73 | 105 |

Table 2.5 Air temperature degree-day accumulation and number of calendar days before 15cm soils thaw from FEF data. Thaw depth indicates the depth for which data was available to estimate 15cm soil temperatures.

| Year | Air Degree-Days | Calendar Days | Thaw Depth (cm) |
|-----------------------|-----------------|---------------|-----------------|
| 2000 | 100 | 34 | 15.2 |
| 2001 | 114 | 37 | 15.2 |
| 2002 | 78 | 25 | 15.2 |
| 2003 | 116 | 19 | 10.1 |
| 2004 | 77 | 24 | 10.1 |
| 2005 | -- | -- | -- |
| 2006 | 102 | 37 | 10.1 |
| 2007 | 101 | 18 | 10.1 |
| 2008 | 103 | 24 | 15.2 |
| 2009 | -- | 39 | 15.1 |
| 2010 | 63 | 24 | 15.2 |
| 2011 | 75 | 26 | 15.2 |
| 2012 | 66 | 15 | 15.2 |
| Average | 90 | 27 | |
| Standard Error | 6 | 2.3 | |

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Chapter 3

Modeling the Usable Growing Season for Interior Alaska Agriculturalists: A Tool for Investigating the Future of High-Latitude Agriculture

3.1 Abstract

Food security is of growing concern as population increases and climate change occurs at local and global scales. While food systems in middle latitudes are vulnerable to uncertain crop success under a changing climate, the dominance of imported food in arctic regions makes Alaskans especially vulnerable to minor disruptions in supply. Increased diversification of and access to local food resources could have the potential to decrease vulnerability in Alaska. Rising air temperatures could provide economic opportunities for Alaskans as arable acreage increases; however little is understood about increases in heat energy experienced in Interior Alaska specific to the agricultural growing season. Understanding the effects of climate change on agricultural systems is essential for planning the future of Alaska's communities, economy, and resource conservation. This paper improves upon the modeling capabilities of Interior Alaska's agricultural growing season for future decades by including seasonal boundaries specific to local agriculture practices. A simple model was developed that used projected downscaled temperature data to calculate growing degree-days within the specific confines of the agriculturalists' growing season for Interior Alaska. This model indicated that growing degree-days could increase 33-50% for early seeded field crop management scenarios and 38-70% for later transplanted vegetable management

scenarios by the end of the 21st century across the model domain. The number of calendar days available for agricultural use increased between 19 and 28 days by the end of the century. This could provide increased economic potential with existing crops and the potential for the introduction of crops currently exhibiting marginal success.

3.2 Introduction

3.2.1 Context

Climate change is expected to impact every corner of the globe. Ecosystem changes including extended growing seasons, retreating mountain glaciers, melting permafrost, changes in migration patterns, altered species distribution, coastal erosion, increased frequency of extreme rainfall events, and over 25,000 more changes in biological and physical systems have been linked to changing climate patterns globally (Rosenzweig et al. 2008; Hayhoe 2010). Since effects are diverse and widespread, even human managed agricultural systems on which we depend will experience significant complications (Chapin et al. 2009). Global effects on agricultural production are expected to cause complications due to changing precipitation patterns, flooding, extended growing seasons, shifting of species or varieties, declining soil moisture, and new or migrating pest and pathogens (Chapin et al. 2009). As some regions expect lengthening growing seasons, there are also regions on the globe whose growing seasons may be shortening due to expected spikes in temperature reaching above growth thresholds (Slingo et al.

2005). Due to these projections, there is increasing interest in gaining an understanding of how these changes will affect different agricultural systems (Juday et al. 2005; Hatch 2011). Understanding what changes may look like aim to enhance the adaptive capacity and resilience of future planning in food security (Anisimov et al. 2007; Lobell et al. 2008; Chapin et al. 2009).

Communities that are currently dependent on distant systems for food resources may face challenges that are two fold; growing conditions of distant food sources are likely to experience changes while similarly, local conditions will experience changes that may or may not be of similar magnitude. Fortunately, these changes may not only present challenges could provide some benefits in terms of growing capabilities (Juday et al. 2005; Chapin et al. 2009). Gaining location-specific understandings of the changes in growing potential could benefit communities' capabilities to harness opportunities presented by climate changes and plan for a dynamically changing future (Chapin et al. 2009).

Communities within Alaska and neighboring arctic and sub-arctic communities are highly dependent on outside resources for food security. For the purpose of this discussion, food security is referred to as "a situation that exists when all people at all times have physical, social, and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life"

(Lobell and Burke 2010). Food security can be divided into three components: food availability (presence of food), access (having means to acquire) and utilization (appropriate nutrient content) (Lobell and Burke 2010).

Short growing seasons and dependence on the homogenized global food system creates high vulnerability with little adaptive capacity and resilience for Interior Alaskans as distant food resources experience climate changes. The large-scale global food system, upon which Interior Alaskan residents depend for food security, is highly vulnerable to all aspects of global change including climate's effects on crops across climate zones and fluctuations in transportation costs (Juday et al 2005; Godfray et al. 2010). The Alaska Farm Bureau estimated that if transportation of goods to Alaska were halted, there would be 2-3 days before grocery store shelves were empty (Meadow 2009). A single disruption in transportation lines or complications due to climate changes in distant locations could leave the residents of Alaska facing situations of food insecurity. With limited annual production within the state, a disturbance to outside resources of food has potential to result in a sudden deficit in every aspect of the aforementioned food security definition: availability, access and ultimately utilization.

Outside of current socioeconomic variables, Interior local agricultural production is relatively limited due to short growing seasons, cold soils, and occasionally early frosts (Loring and Gerlach 2009). As there will be many challenges presented by climate

change, there may also be opportunities for Interior Alaska growers through seasonal extension and annual temperatures (Juday et al. 2005; SNAP 2009; Anisimov 2007).

When moisture and nutrients are not limiting, biological processes such as germination, growth, and development are generally dependent on temperature (Gliessman 2007).

Because of temperature's inherently profound effects on growing capabilities, Interior Alaska agricultural production may eventually be forced to re-evaluate agricultural production methods.

Understanding how Interior Alaskan growers are limited and how these limitations may change has the potential for increasing future planning. Mapping out expected changes in the growing season for Interior Alaska agriculturalists may in turn reduce the vulnerability of the region's food security by enhancing local production. To achieve food security that is robust to both local and global disturbances, Alaskans cannot solely rely on either local or global resources. Developing an understanding of what climate change may mean for agricultural production in Alaska will help farmers and gardeners develop adaptive capacity and integrative management plans for enhanced and changing production capabilities.

3.2.2 Objectives/Questions

This research investigates the potential effect of rising air temperature on future growing season potential in Interior Alaska. The central question of this research is: Can

a model be created that projects degree-day totals within the specific confines of the Interior Alaska agricultural growing season? Subsequent questions include: 1) How many agricultural specific degree-days could Interior Alaska agriculturalists experience by the end of the century? 2) How will climate change potentially affect the length of the agricultural growing season of Interior Alaska? 3) What do these changes suggest for the expansion of new crops or the effects on currently successful crops?

To answer the aforementioned questions, a simple model was developed to calculate Interior Alaska agricultural growing season degree-days. Within model calculations, the projected length of the agricultural growing season was also estimated using agricultural season parameters. The scenarios presented in this paper aim to contribute to the conversation about how increasing seasonal heat energy may affect the potential for crop survivability and success. As the length of growing season and number of growing degree-days can be used in comparison to known crop growing requirements, results are used to compare basic plant degree-day requirements to investigate whether or not new crops may be successful in the future.

3.2.3 Study Area

The spatial domain of the model in this paper encompasses a 8,800 km² region around Fairbanks Alaska, the largest urban hub in the Interior. Other communities within the model domain include Ester, North Pole and Salcha (Figure 3.1). The climate of this region exhibits long cold winters with relatively short summers. Fairbanks

experiences average monthly temperatures ranging from -22 to 17°C in January and July respectively (ACRC 2013) with precipitation ranging from 6 to 55mm in March and July respectively (ACRC 2013).

The warm dry summers experienced in Interior Alaska led to the labeling of the Interior as the “breadbasket of Alaska” and was the site of the first Interior Alaska experiment farm at the turn of the 20th Century. Although there are many crops that are successfully raised in Interior Alaska, growers experience a relatively short growing seasons compared to more temperate regions. Over the last 30 years, frost free (above 0°C) days ranged from 86 to 144 days with a median value of 115 days (ACRC 2013). As indication that longer seasons would be beneficial to agriculturalists, numerous methods are used in the Interior in attempt to extend the growing season (Holloway 1993). Projected changes in climate have the potential to provide extended seasons and therefore increased potential for economic opportunity for farmers, less dependence on outside sources, and allow for crops that were once unsuccessful to become feasible (Juday et al. 2005).

3.2.4 Climate Change in Interior Alaska

Among many changes and variables that may be associated with climate change over the next century, most certainty exists in the projection that temperatures will change (rise) quite dramatically, especially in the Arctic (Walsh et al. 2008). Climate

models currently indicate a polar amplification of greenhouse-driven climate change will occur, meaning that changes in Arctic climate are expected to be greater than those experienced at lower latitudes (Walsh et al. 2008; Chapin et al. 2009; Wolken et al. 2011).

From 1951 to 2001, the mean annual air temperature in the Interior of Alaska has increased an average of 1.3°C, with most of the warming occurring in the winter (Wolken et al. 2011; Hartmann and Wendler 2005). These observed increasing trends are not expected to slow down. Northern regions are expected to increase 1.5-4.5°C of the global mean by the end of the century (Euskirchen et al. 2006). Air temperature in Interior Alaska is expected to rise 3 to 7°C by the end of the 21st century (Wolken et al. 2011; Walsh et al. 2008; SNAP 2009). Fairbanks' air temperature is expected to increase 10-15°C in the winter and 5-10°C in the summer (SNAP 2009 a). It has been estimated that from the 1940's to the 1990's across Alaska and Canada growing season lengthened 2.6 days per decade (Euskirchen et al. 2006) and Anisimov et al. (2007) expect growing seasons to be extended 3 days per decade. The average number of frost free days in the Arctic may increase between 20-40 days by the end of the century (SNAP 2009).

Precipitation is a more challenging variable to project with the same level of confidence as temperature (Chapin et al. 2009; SNAP 2012a). However, precipitation in Interior Alaska has increased 1.4mm/decade over the past 50 years (Wolken et al. 2011) and is projected to continue to increase toward the end of the century. This increase in

precipitation is expected to occur mostly in the winter and has therefore led to projections that the minimal increase in precipitation will result in an overall loss of water through evapotranspiration in the warming summers (Juday et al. 2005; Wolken et al. 2011; Chapin et al. 2009; SNAP 2009). This potential decrease in available water for crops could prove to be a disadvantage associated with climate changes in non-irrigated crops, however irrigated crops would still likely benefit from increased season length and heat energy (Juday et al. 2005; Chapin et al. 2009).

Estimates of how air temperatures may change over the next century has previously provided insight into how large scale changes may affect agricultural production (Chapin et al. 2009; Juday et al. 2005). In the Arctic Climate Impact Assessment, Juday et al. (2005) estimated that crops currently on the edge of being successful in Alaska, such as canola, may be more probable by the end of the century based on estimated projections of growing degree-days. As these estimates provide information for changes over large regions and are important discussion points for changes in Arctic regions, these estimates lack adequate investigation into how degree-days will change within the specific confines of the growing season for Interior Alaska agriculturalists.

Previous estimates assume that the growing season is defined by daily averages reaching above or below the freezing disregard consideration of the sensitivity of agricultural crops. These studies also do not consider the restraints due to soil

temperatures and processes which could also affect the feasibility of agriculture due to climate changes (Gitay et al. 2001; Juday et al. 2005).

3.2.5 Degree-Day Concept

Since Reamur coined the idea of heating units in 1730, the agricultural sciences have used the concept in terms of 'growing degree-days' (GDD) or 'growing degree units' to improve the predictability of phenological stages of crop development (McMaster 1997). Growing degree-days (GDDs), a measure of accumulated energy (Juday et al. 2005), have proven to be a superior method of predictability over counting calendar days for crop planning (McMaster 1997; Juday et al. 2005). They are used to predict timing of growth stages, planting, fertilization, harvest coordination (McMaster 1997) and are generally calculated using ambient air temperature. Conventionally, daily values are calculated as the average of the maximum and minimum temperature less a base temperature below which the given species of interest cannot grow. The equation for GDDs is:

(3.1)

$$GDD = \frac{T_{Max} + T_{Min}}{2} - T_{Base}$$

where DD is a degree-day, T_{Max} and T_{Min} are the daily maximum and minimum temperatures (°C) respectively and T_{Base} is the temperature below which the organism of interest cannot grow.

This daily value is added to the total degree-day sum over a defined growing season. Defining this growing season is done in a number of ways depending on the intended application of the degree-day calculation. The beginning date, termed the biofix date, varies with species and is commonly determined by specific biological events such as planting date or pest occurrence (Miller et al. 2001). Beginning and ending accumulation periods are also commonly determined by temperature thresholds or calendar days to estimate seasons.

Growing degree-days are effective predictors of plant growth under optimal conditions; however, accuracy decreases if stresses such as soil temperature, nutrients, or moisture stress are present (Bootsma 1984; Juday et al. 2005). They can also vary depending on crop, location (Sanderson et al. 1994), photoperiod and growth stages (Jenni et al. 2000; Juday et al. 2005).

Increased temperature and shorter periods of snow cover may present earlier planting dates and result in increased seasonal degree-days (DDs). Seasonal DD values can help a farmer determine whether or not a crop is feasible given one known basic climatic variable, temperature (Juday et al. 2005). Using the least uncertain projected climate variable, temperature, projections of DDs provide insight into the feasibility of crops that were once historically not possible for Interior agriculturalists (Juday et al. 2005; Hatch 2011).

3.2.6 Climate Data

Scenarios Network for Alaska and Arctic Planning (SNAP); a University of Alaska Fairbanks associated research institute, produces downscaled future climate data specific to Alaska. Large scale data utilized by SNAP originated from the Intergovernmental Panel on Climate Change (IPCC) global climate models (GCMs). The IPCC provides peer reviewed global climate models (GCMs) that project global estimates of climate over the next century. Coarse scale IPCC GCM projections have been adequate in terms of examining large scale climate patterns, but do not allow for detailed analysis on smaller scales such as a region (Hayhoe 2010). This makes it very difficult for scientists to make reliable projections for local regions, where changes are experienced by the individual, family, or community. Climate data downscaling methods have been used to create more spatial accuracy (Hayhoe 2010).

SNAP employed climate model downscaling methods to produce 2km spatial scale climate data for the State of Alaska. To downscale GCM data for Alaska, Dr. John Walsh and a team of investigators chose 15 GCMs from the IPCC Fourth Assessment Report (AR4) that were used in the Third Coupled Model Intercomparison Project (CMIP3) (Walsh et al. 2008). The models were evaluated based on how well they matched Alaska and Greenland historical climate data over the time period 1958-2000 (Walsh et al. 2008).

Previous research and Walsh's results indicated that using multiple or a hierarchy of models for analysis can enhance the ability to create robust projections (Walsh et al. 2008; Hayhoe 2010; SNAP 2012b). With this consideration, the top 5 ranking models were chosen from Walsh's evaluation.

GCM data were downscaled over Alaska using the "delta method." The delta method is an effective, simple and a common way climate data is downscaled for ecological applications (Hayhoe 2010; SNAP 2012b). The delta method calculates the difference (the delta) between historical climate data and future climate conditions simulated by a GCM. This difference is then added (for temperature) or multiplied (for precipitation) to historical monthly or daily observations to simulate future conditions that include modeled climate changes (Hayhoe 2010; Hayhoe 2011; SNAP 2012b). Since observed data is generally on a much smaller scale than the GCM outputs, this produces a more site specific dataset of simulated climate data for impact analysis.

The primary historical dataset used for the downscaling process was the Parameter-elevation Regressions on Independent Slopes Model (PRISM) data from Oregon State University. PRISM data is the highest quality spatial climate data currently available (SNAP 2012b). PRISM includes important local climate altering features such as elevation, proximity to coastlines, and even local climate knowledge at a scale of 2 km over Alaska and Canada (SNAP 2012b). SNAP uses temperature and precipitation data at the 2 km scale from 1961-1990 and 800m scale from 1971-2000 (SNAP 2012b).

SNAP downscaled GCMs were “backcasted” by replacing future climate data inputs with the greenhouse gas conditions of the 1980-2000 period in order to simulate historical data. Generating model runs for past time periods and then analyzing the statistical relationship between observed weather patterns and model outputs provided a viable way of validating the accuracy of the downscaled model outputs with observational data (SNAP 2012a). Therefore, SNAP compared backcasted GCM output to historical weather data from 32 selected weather stations around the state. Comparisons were based on four temperature and precipitation metrics: monthly mean values, seasonal (month-to-month) variability, annual (year-to-year) variability, and long term climate trends (SNAP 2012a).

Analysis of downscaled model outputs led to the conclusion that the seasonal variability, interannual variability and the ability for models to project long term trends performed well when compared to historical weather station data (SNAP 2012a). However, temperature projections outperformed precipitation projections consistently through each test. This can be explained by natural variability in precipitation events throughout the year causing massive alterations to monthly averages and to the reliance of this analysis on a relatively small number of weather stations for the area being assessed (SNAP 2012a). The model presented in this paper exclusively uses projected temperature data and uses previous modeling efforts in precipitation modeling as discussion points in subsequent sections.

This research expounds on previous growing degree-day analyses in Interior Alaska by defining the growing season specifically within agricultural growing season constrictions. The model defines these seasonal constrictions based on parameterized beginning and ending dates using farm observations in Interior Alaska. This study is also unique for Interior Alaska in that it uses downscaled climate data that includes considerations of topographical factors across space. Using the accumulated value of heat energy (degree-days) allows for the comparison of results to previous studies and utility for local farmer stakeholders as growing DDs are commonly used to estimate crop feasibility.

3.3 Methods

3.3.1 Model Description

To assess future agricultural growing conditions for Interior Alaska, a simple model was developed utilizing downscaled projected climate data. This model projects the usable growing season for Interior Alaska to the end of the century. That is, the model projects the length and energy accumulation within the specific seasonal constrictions for agricultural production. The model uses a set of seasonal boundary conditions determined by regional observational data. Future projections are driven by the best available future climate data. The primary result of the model calculations present seasonal accumulated heat energy values: degree-days. To satisfy the objective of representing the growing season in terms of agricultural production, the day of

planting and the first day of frost were used as the conceptual beginning and end of the agricultural season. Degree-days calculated within these boundaries were termed usable degree-days (UDDs) and will be referred to as such from here on. The equation for usable degree days is:

(3.2)

$$UDD = \sum_{i=\text{planting date}}^{\text{frost}} GDD$$

where the accumulation of growing degree-days (GDDs) occurs between the days of planting of the crop to the first frost.

Modeled UDD calculations were computed using projected average decadal monthly values. The boundaries of the usable growing season are determined using interpolated daily temperature values from monthly values using the spline technique within the Python Scientific Package. Daily DD values are accumulated using interpolated daily values within the confines of the defined agricultural growing season.

Because daily maximum and minimum temperatures were not available as the conventional degree-day calculation requires, interpolated daily temperature values were considered the best estimate of daily average temperatures and were accumulated for each day within the growing season boundaries. These calculations are

computed within each of the 2208 2km pixels within the model domain (Figure 3.1) producing a spatially explicit set of UDD values for a region within Interior Alaska.

In order to estimate the biofix date (the planting date), a historical dataset was used to estimate the number of degree-days that occur between snow melt and planting dates at the University of Alaska Fairbanks (UAF), Fairbanks Experiment Farm (FEF). Temperature thresholds of 0°C, or snowmelt, are easily calculated from climate data but do not represent a feasible day of planting for agriculturalists. Therefore the number of degree-days that accumulate between snowmelt and planting date were calculated to estimate a planting date for two management scenarios: early seeded field crops and late transplanted vegetable plots. Within these two management scenarios, the minimum, average and maximum FEF degree-day observations between snowmelt and plant date were selected to provide a broad scope of possibilities within each crop management scenario.

Once the daily temperatures exceed 0°C, a predetermined number of spring lag degree-days are accumulated based on interpolated daily projected temperature data. Once the lag for the management scenario of interest is reached, a planting date is estimated (Figure 3.2). To assure that the model accounted for the time it takes for spring soil moisture to become optimal for preparing the fields, the minimum number of observed days between snowmelt and planting date at FEF was selected as the minimum amount of time that can pass before a planting date can occur. If the spring

lag DDs are satisfied before 11 calendar days have passed, the biofix (planting) date does not occur until the 12th day after modeled snowmelt to account for soil thaw and saturation. From this planting date, daily interpolated DD values are accumulated until the seasonal termination date is reached by the first day of fall frost (Figure 3.2). This accumulated value is presented as the total growing season UDD value as the decadal average UDD value for the corresponding decade.

3.3.2 Model Inputs

Model inputs include projected decadal monthly average temperatures, temperature (°C) for snowmelt threshold, spring lag degree-day value, and day of frost temperature (°C) threshold. Scenarios Network for Alaska and Arctic Planning (SNAP) data were used as the primary resource of projected climate data. SNAP's projected decadal monthly averages project temperature data at a 2km spatial scale enabling the determination of snowmelt, spring lag DDs, day of frost and ultimately UDDs for each pixel within the model domain.

3.3.3 Parameterization

This analysis parameterizes usable growing conditions for Interior agriculturalists by estimating a seasonal beginning point (planting date) and terminating point (estimate of a frost occurrence). Using snowmelt coupled with a calculated spring lag is intended to parameterize important factors in determining planting dates and usable growing conditions such as soil temperature, ability to till soil, air temperature minimum

requirements and local production management strategies. Snow melt was considered the most reasonable starting point for spring DD accumulation as the insulative and albedo factors of snow cover would be negligible. However, a specific estimator of snow melt was not available. Instead, day of thaw has been used as a basic estimator of snow melt. Day of thaw is the day where the average daily temperature exceeds 0°C but will be referred to as snowmelt from hereon.

The spring DDs that provide an estimate of a planting date were calculated with a 6 (vegetable) and 8 (field crops) year dataset of observed planting dates collected in the lower fields of the FEF. An estimate for both vegetable crops and field crops were calculated to cover a range of management scenarios within the Interior of Alaska. These data were used to calculate the average DDs that accrue between snowmelt and planting dates for early seeded non-irrigated field crops and late transplanted irrigated vegetable crops. For each management scenario, the model was run for a minimum, average and maximum number of spring DDs based on observed data at FEF from 1991-2012.

The method used for calculating the day of frost was adopted from the Agriculture and Agri-Food Canada 'effective growing degree-day' procedure by Sly et al. (1971) (Marshall et al. 1999). The model presented in this paper used a modified version of the first frost estimate procedure developed by Sly et al. (1971) that most accurately represented 30-year average historical datasets. This procedure takes into

consideration elevation, latitude, seasonal averages and extremes to estimates a lag on either side of 5.56°C daily average temperature to determine the first day of frost.

Exploring this method suggested that using the point where daily average temperatures reach 5.56°C was an acceptable estimate of frost for the modeled region. The model assumes that when the average daily temperature reaches 5.56°C, the pixel has experienced a frost and the growing season UDD calculation ends.

3.3.4 Model Validation Procedures

Since historical observations of planting dates and UDDs are lacking in weather station data, two backcasting exercises were completed to investigate secondary driver accuracy: one that compared historical model outputs to FEF observations and one to collected observations from farms within the model domain. These comparisons were made to check model accuracy for both FEF (where the estimators originated) and for farms with differing biophysical conditions (elevation, soil type, farm management etc.) that could check for bias or error in modeled UDD values.

3.3.5 Weather Station Comparisons

To identify the accuracy of the model in projecting UDD estimates under future conditions, historical weather station observations were collected from the Western Regional Climate Center (WRCC 2006) and used to compare historical model outputs. Five weather stations were chosen within the model's spatial domain that had between 25 and 30 years of consistent observations (less than 4% missing values with the

exception of Salcha weather station). Validation weather station locations can be seen in Figure 3.1.

Because of their purely biophysical nature and the availability of local historical observations, snowmelt and frost date were the two variables considered to be most verifiable. If these two endpoints were projected with reasonable accuracy, it was assumed that secondary boundary conditions would capture the range of future results for farming growing seasons via running the model for a range of observed planting condition scenarios.

To perform the historical or ‘backcasting’ exercise, downscaled historical Climate Research Unit (CRU) data for the model domain was used to calculate backcasted model outputs. Downscaled historical CRU data from the University of East Anglia in England Historical are based on 3000 monthly temperature stations over land and additional stations over the sea (SNAP 2012b). Pixels within the model boundaries that overlaid the location of each of the 5 weather stations were used to compare backcasted results to historical observations. Model results were compared to 30-year averages of weather station observations of snow melt and frost dates (Tables 3.1 and 3.2). Downscaled CRU data was only available up to 2009 providing a thirty-year comparison from 1980-2009.

Within observed data, snow melt was considered to be the first day snow depth was equal to 0cm in the spring. Frost date was determined to be the day the average

temperature dropped below 5.56°C. These station observation comparisons not only provided a glimpse of the climatic accuracy of the model but also spatial accuracy.

Day of frost was more accurate than snow melt dates when comparing the 30 year average of historical model output results to historical station data (Table 3.2). Differences between modeled and observed days of frost ranged from 0 to 3 days averaging a difference of 2 days across the station pixels. Modeled data projected the date of frost to be 3 days later than observed day of 5.56°C to 1 day before the observed frost date.

As weather station data lacked a specific frost observation, observed frosts days within FEF datasets were used to analyze 5.56°C as an estimator of actual frost occurrences. Five of the twelve frost observations predicted the exact day of frost and the remaining years that did not predict the exact day only deviated an average of 3 days. With this reasoning, the frost date estimate was defined as the day where the average daily temperature fell below 5.56°C.

Thirty year average historical (CRU) model outputs for snowmelt were 11 to 14 days earlier than the observed day of snowmelt. As this could affect UDD calculation, Table 2 displays the discrepancy in observed degree-days in this range of 11 to 14 calendar days. Degree-days range from 11 to 21 and were calculated using 30-year

average daily temperatures from the same datasets used for frost date comparisons at five weather stations.

3.3.5. FEF Pixel Comparisons

Using annual historical (CRU) data, historical model runs were calculated using the two extremes of the scenario range within management groups: the minimum and maximum spring lag degree-day inputs. Basic differences between modeled (CRU) and observed results were calculated by subtracting the difference between calendar days for the variables snowmelt, plant date, and frost; and degree-days for UDDs comparisons. UDD observations were calculated using the closest 1st order weather station data due to lack of on-site data collection at sample farms. The Ester weather station was used to estimate UDDs for both Calypso Farm and Ecology Center's and Cripple Creek Organic's. As the exception, FEF had on-site weather station data allowing for spatial accuracy.

Results for FEF comparisons are displayed in Table 3.3. For the low spring lag scenario, the category freeze date was the only input variable that had a mix of positive and negative discrepancies. Negative differences simply signify that the modeled date was projected to be earlier than the observed date or that the modeled UDD values undershot (was less than) the observed farm values. For each year of observation, modeled snowmelt date, early field start date, late vegetable start date, early crop

UDDs and late crop UDDs were projected earlier than observed farm values. Snowmelt date was projected an average of 9 days earlier with a range of 3 to 15 days (n=12). For every observed year, crop start date was projected later than observed dates, averaging 6 days early and ranging 2 to 9 days early (n=5). Average difference between modeled and observed late vegetable planting dates was 4 with a range of 2 to 12 days (n=3). Date of freeze exhibited mixed results of early or late modeled results with the majority of the modeled dates occurring after the observed frost. The average difference between modeled and observed historical frost dates was 7 days with a range of 1 to 16 days (n=10). The average difference between modeled and observed early field crop modeled UDDs was 179 UDDs with a range of 73 to 247 UDDs (n=4). Modeled historical late vegetable crop UDDs were all larger than the observed late UDD values. Modeled historical late vegetable UDDs were on average 193 UDDs larger than observed ranging from 133 to 258 UDDs (n=3).

For the maximum spring lag scenario, the categories of late vegetable start date, frost date, and early crop UDDs all had a mix of positive and negative results (Table 3.3). On every occasion, modeled snowmelt date was projected earlier than observed snowmelt averaging nine days early and ranging from 3 to 15 days early (n=12). For every observed year, early crop start date was projected later than observed dates, averaging 6 days (range 3 to 10 days (n=5)). Late vegetable crop start date was mixed with one of the three observations occurring before the actual planting date. Average

absolute value of difference between modeled and observed late vegetable planting days was 4 with a range of 1 to 6 (n=3). Date of frost also exhibited mixed results of early or late modeled results with the majority of the modeled dates occurring after the observed frost. The average difference between modeled and observed historical frost dates was 6 days (range of 1 to 16 days (n=10)). Early field UDDs were mixed with one of the four modeled values being less than observed UDDs. The average difference between modeled and observed early field crop modeled UDDs was 85 UDDs with a range of 44 to 134 UDDs (n=4). Modeled historical late vegetable crop UDDs were all larger than the observed UDD values. Modeled historical late vegetable UDDs were on average 59 UDDs larger than observed ranging from 12 to 111 UDDs (n=3).

Results for comparisons between other farms within the model domain are presented in Tables 3.4 and 3.5. Considerations for other farm comparisons include a lack of observations (years), quality of observations (inconsistencies in human observations and estimations), discrepancies between weather station and farm physical characteristics (elevation, microclimate effects on-site, etc.). The Ester weather station used to estimate UDDs is much lower in elevation than Calypso Farms or Cripple Creek Organics (Table 3.6) potentially misrepresenting the actual UDDs experienced at the farm.

Since management is different at each farm, early field crops were categorized as those that were directly seeded and late vegetable crops were those that were

transplanted as seedlings in the field. The higher elevation of these farms extends their season since frosts generally stop occurring much sooner in the spring than the lower elevation farms (Susan Willsrud, Personal Comm., May 16, 2013). Therefore the day direct seeding can occur (field plant date) appears to be a better estimate for both field and vegetable plant date for farms of higher elevation making the two separate scenarios that are useful for lower elevation farms potentially obsolete for higher elevation farms. Further data collection at multiple farms would help hone this estimation.

3.4 Results

3.4.1 Model Projection Results

Early field crop scenario UDDs were projected to increase by 33 to 50% across all pixels representing a 580 to 632 increase in UDDs over the coming century (Table 3.7; Figure 3.3). Late vegetable crop scenarios projected UDDs increasing by 38 to 63%, representing 572 to 637 UDDs of change across the modeled domain (Table 3.7; Figure 3.4).

Each pixel within the model domain changed at slightly different rates. Increases in field crop UDDs from 2010 to 2090 ranged from 580 to 630 UDDs across the pixels within the model domain (Figure 3.5). Largest changes in UDDs are projected to be in

the low lying areas within the modeled area (Figure 3.5). Pixels exhibiting absolute largest changes were centered in the region of Fairbanks, and Ester.

To demonstrate change of a known farming location, the exact pixel above FEF was chosen to compare UDDs at the beginning and end of the season. This pixel was in the region of some of the largest changes by the end of the 21st century (Figure 3.5). The projected UDDs were 1714-1828 UDDs for the decade of 2010-2019 and 2330-2451 UDDs by the decade 2090-2099 over the low, average and high scenarios for early field crops (Figure 3.6). Growing season length for the pixel ranged from 125-138 days in the 2010-19 decade to 146-159 days in the 2090 decade (Figure 3.7). Vegetable growing season lengths change relatively similarly but were 22-28 days shorter than field crop growing seasons due to the later planting date (Figure 3.7).

Model results suggest that the day of snow melt may become 9-14 days earlier in the spring. Days of frost were projected to become about 9-11 days later in the fall (Table 3.8). Planting dates for early crops were projected to become 9-16 days earlier across all scenarios of spring lag (Table 3.9). Similarly, planting dates for late crops were projected to become 11 to 18 days earlier in the spring (Table 3.10). This lengthening of either side of the growing season resulted in an overall lengthening of the growing season from plant date to frost of 19 to 27 days for early crops and 20 to 28 days for late crops across the low, average and high scenarios (Figures 3.7, Tables 3.9 and 3.10).

3.4.2 Sensitivity Analysis

Each model input variable was increased and decreased at reciprocal intervals to test the overall sensitivity of the model's UDD outputs to changes in model inputs. The variables snowmelt and frost were altered by ± 1 , 3, and 5°C. The two spring lag DD variables were altered by ± 10 , 30 and 50%. This sensitivity analysis demonstrated that the model had varying sensitivities to changes in each input variable (Tables 3.11 through 3.13).

Overall the model was least sensitive to changes in the variable estimate of snowmelt. A positive and negative 5°C shift in the snowmelt temperature threshold produced a percent change in vegetable UDDs of 2.74 and 1.83% respectively (Table 3.11). A positive and negative 5°C shift in the frost estimate resulted in a 2.67 and 9.26% change in vegetables UDDs respectively (Table 3.12). The vegetable UDD output was almost exclusively more sensitive than field crop UDDs to changes in all estimator variables. The only instance where field crop UDDs appeared to be more sensitive than field crop UDD outputs was with the first incremental changes in the estimate variable snowmelt. Vegetable UDD results were more sensitive to incremental change in spring lag DDs than field crop UDDs. A 50% increase in spring lag DDs for both field and vegetable crop management scenarios resulted in a 2.14 and 14.22% increase in field and vegetable UDDs respectively (Table 3.13). The vegetable management scenario starts much later than the field crop which coincides with higher temperatures on the

annual temperature curve (Figure 3.2). The vegetable growing season is, consequently shorter and has less UDDs than the field crop growing season. Changing the starting date where daily degree-day values are relatively high is likely reason for the heightened sensitivity of late vegetable UDD outputs.

3.5 Discussion

3.5.1 Model Driver Uncertainties

Climate models in particular have a layered level of uncertainty due to the complex nature of their creation, use and greenhouse gas emissions scenarios. However, confidence in the estimates utilized in this model are attributed to the IPCC's rigorous GCM analysis, SNAP and Walsh et al. (2008) investigations in Alaska-specific analysis and downscaling processes, the choice of five model average data as a primary driver, medium emissions scenario and the basics of GCMs foundation in known physical processes. GCMs models have proven to provide reasonably certain insight into the future conditions of Earth's climate (Randall et al. 2007).

Choosing high quality datasets and disclosing uncertainty and assumptions allows climate change discussions to move forward with known confidence and transparency. The Intergovernmental Panel on Climate Change (IPCC) has assessed numerous GCMs providing the global scientific community with foundational peer reviewed climate science and data. SNAP data used in this analysis was based upon the IPCC's Third Assessment Report (TAR). The TAR is the most updated analysis report on

GCMs to date and is considered the reputable global resource for GCM analysis. The IPCC conducts multi-model intercomparisons and routinely evaluates the effectiveness of GCMs in order to assess and improve the capability of climate models (Randall et al. 2007).

Confidence that these models can provide credible quantitative estimates of future climate conditions comes also from their foundational theories and ability to project both past and current climate (Randall et al. 2007). GCM's foundational theories and equations are based on established physical laws of the Universe such as the laws of thermodynamics, conservation of mass, energy and momentum. These well-established physical laws are then coupled with additional real world observations to provide the best possible representation of reality (Randall et al. 2007). These monitored GCMs are the foundational climate projection data most climate assessments are based upon; including SNAP projects.

Relying upon the results of multiple GCMs reduces uncertainty in climate projections and produces robust projections on which to base smaller-scale impact analysis for Alaska (SNAP 2012a). The five best performing models are used in this model to project climate in coordination to reduce the possibility of errors associated with individual model biases (SNAP 2012a; Hayhoe 2010; Walsh et al. 2008). Climate scenarios are based on different ranges of estimated atmospheric carbon dioxide

concentrations for future decades. This research used the a1b scenario to provide a mid-range estimate of expected climate changes.

The main assumption within this model is that the climate data utilized accurately projects future conditions. SNAP data and GCM models have been checked extensively for their accuracy using the only observational data available, historical data. Model backcasting provided assurance that the models project averages that reasonably represent reality when given past data (SNAP 2012a). The subsequent assumption is that the climate model estimates future conditions to the same extent that it does historically. Since future observations do not exist, multiple scenarios were conducted within the secondary drivers to provide a range of possible futures. Model projections are not to be considered predictors of future conditions for specific locations, but indicators of future trend possibilities.

3.5.2 Secondary Driver Discussion

Beyond the assumptions and uncertainties inherent in the primary driver climate data, there are considerations for the secondary model inputs. Secondary inputs include the estimation of snowmelt thresholds (°C), planting date DD lag and the frost occurrence threshold (°C). With limited data, secondary drivers were intended to parameterize the complex set of social and biophysical variables associated with farming in Interior Alaska that would otherwise be very complex to model. These secondary drivers are based on the University of Alaska Agricultural & Forestry Experiment Station

(FEF) historical dataset and a short two year dataset that extensively documented air and soil temperatures under different crop management types.

Because the spring degree-day lag was based on FEF data, conditions of the FEF are inherently assumed to be representative of all Interior Alaska growing conditions. Further research and larger datasets could improve upon this assumption by including more detailed effects of aspect and elevation beyond what is parameterized in the downscaling process using PRISM data. Further research could also provide a more robust estimate of planting date, frost date and growing degree days by collecting extensive data that cover a more broad range of growing conditions and management systems in Interior Alaska over a longer time span.

The day farmers can plant in the Interior is not as simple as planning to plant on a specific day or even once temperatures reach a certain point. Agriculturalists must be flexible and are in a constant guessing game with the season's weather and many other factors. With such short and intense growing seasons it is of utmost importance that crops are in the ground as soon as possible in order to utilize all degree-days possible. The day a farmer plants depends on countless factors that are not only environmentally dependent. These factors include but are not limited to air temperature, soil temperature, soil moisture, planting methods, availability of resources, seedling development, and the type of crop. Because most of these factors lack a sufficient dataset and are too complex to project into the future using only climate data, farm

observations were considered to be useful in encompassing all of the aforementioned factors in plant date considerations. With these thresholds acquired, it was possible to use future temperature datasets to provide estimates of a day where planting crops would be feasible for two main management types: directly seeded field crops and vegetable crops.

The DD values used to estimate a planting date encompass not only climate data but also naturally include all the factors mentioned previously since the dates provided were observed dates from a working farm experiencing all of the possible bio-physical and socio-economic factors. This estimate provides an average length of time that all mentioned factors can affect planting dates. Each farmer has his/her own method for planting and FEF is known to be one of the most opportunistic farms, planting as soon as the soil and air temperatures permit them to plant (Personal comm., Seefeldt November 20, 2012). This model's secondary drivers are based on one farm's observations, but because of this farming management style, its estimates will provide generous UDD projections that are assumed to be mainly based on environmental conditions.

Basing the secondary driver of this model off of a small dataset has its limitations but the value of this model is presented to open new avenues of discussion and identify areas of research that need to be explored for future agricultural production planning and modeling. By demonstrating the strength of the model's ability to project the biophysical boundaries of this model (snowmelt and frost) historically, the secondary

boundaries ability to produce reasonable estimates within these seasonal boundaries are considered to encompass a range of growing scenarios within these known and validated boundaries.

Although the snowmelt estimate was projected to be earlier than the observed snow melt date in the backcasting exercise, its overall effect on UDDs was minimal (0.4-2.5% proportional to total UDDs). The sensitivity of UDDs to the snowmelt date was lowest of all the variables and considered to be a reasonable estimate for the purpose of this discussion. The model produced the day that daily air temperatures dropped below 5.56°C within 0-3 days compared to 30 year averages. Although actual observations of frost were limited, verification from frost observations acquired from FEF provided confidence in 5.56°C as a reasonable estimate of a season-terminating frost date.

3.5.3 Crop Feasibility Considerations

Further assumptions made in this model relate to future agricultural productivity. Discussions surrounding model results assume that current growing conditions in the Interior remain productive in order to use the current growing capabilities as indicators of future productivity. Soil properties including texture, thermal conductivity, nutrient availability, and water holding capacity are assumed to remain relatively constant keeping the productivity of the soils at a relatively constant state outside of moisture and temperature variables. There is however, evidence that

soil properties will change with climate and may cause future limitations (Juday et al. 2005).

It is conceivable that warmer soils may mean that farmers can work the soil earlier in the spring not only extending the growing season, but also affecting soil processes. Increased soil temperature will also provide the opportunity for increased decomposition in the soil (Euskirchen et al. 2006). This is generally a benefit to the farmer who needs nutrients to be readily available to the crop throughout the season. Increased microbial activity in the soil helps soil fertility and may provide more opportunity for organic gardeners to incorporate their own compost in the soil for fertility and sustainability purposes.

Another challenge of climate change may be the combined impacts of warmer temperatures and inadequate increases in precipitation (Juday et al. 2005; Anisimov et al. 2007; Zhang 2011). One assumption of this model is that soil moisture and precipitation will remain relatively constant to the current conditions for non-irrigated agriculturalists. It has been projected that the earlier onset of the non-frozen season promotes annual evapotranspiration in colder areas and appears to increase drought stress where water input is limiting (Juday et al. 2005; Anisimov et al. 2007; Zhang 2011). The need for irrigation may increase if the timing of precipitation is not beneficial for non-irrigated crops. SNAP projections for precipitation in Fairbanks show increases

for late summer precipitation. This can be beneficial for some crops such as carrots or potatoes but potentially harmful for those crops that need moisture in the beginning of the season but hot dry periods late in the season to fully develop; for example, barley or corn.

The extension of the growing season could potentially make way for increased economic opportunities for farmers by increasing the length time of farm profitability. A survey of farmers in Interior Alaska found that community supported agriculture (CSA) farms were experiencing on average 13 weeks of production, ranging from 7 to 22 weeks across all farmers interviewed (Caster 2011). Farms with the most weeks of profitability were those with season extension infrastructure (greenhouses, mechanized farm equipment, and cold storage) while farms without season extension infrastructure were those with the shortest windows of profitability (Caster 2011). With the usable growing season projected to increase by 9-11 days at the beginning and end of the growing season, farmer's window of opportunity may expand enough to create new economic opportunities.

These opportunities in increased profit may reduce some of the socio-economic constraints on farm expansion in Interior Alaska. This same survey documented that problems farmers face in the Tanana valley for farm expansion include costs of start-up infrastructure, fuel, labor, electricity, land and marketing (Caster 2011). CSA farmers

listed non-biophysical reasons for constraints on business to include a lack of local processing facilities, competition with imported food resources, and access to capital or financing terms (Caster 2011). An increase in economic opportunity will only be effective to break thresholds of farm expansion success if in conjunction with help of consumers and institutional support

With increasing uncertainty associated with food security in the Interior, integrative and resilient food systems must be implemented in ways that are unique to each community and region (Anisimov et al. 2007). Resilience and adaptive capacity depend on ecosystem diversity and the adaptability of the governing institutional rules that govern local social and economic activities of a given location (Adger 2000; Anisimov et al. 2007). With institutional support and flexibility, adaptive capacity and resilience could be enhanced by reducing these socio-economic constraints experienced by farmers. The combination of institutional support and harnessed opportunities presented by changes in the biophysical realm of climate, could increase access to food locally and may diversify the Interior's food resources.

Focusing on the biophysical properties alone, there has been speculation that crops that were once not successful in the Arctic may become feasible due to increases in heat energy in future growing seasons. Similar growing degree-day modeling exercises for regions overlapping this model's domain have examined crops that may

become possible due to increases in seasonal heat energy. Conclusions of previous examinations include that crop production could advance northward; crops currently suitable for parts of the Arctic may now be suitable as far north as the Arctic Circle, and yields may increase with the availability of longer-season varieties (Juday et al. 2005; Sparrow et al. 2007). Furthermore, perennial forage crops may produce more yields with longer time spans of harvest availability (Sparrow et al. 2007).

Understanding the limitations of using growing degree-days at high latitudes is essential for interpreting previous scenario analyses and the results presented here. Growing degree-days are useful tools for predicting crop growth and maturity stages but may vary depending on many factors including cultivar, location (Jenni et al. 2000; Juday et al. 2005), or photoperiod (Juday et al. 2005). High latitude degree-day analyses face challenges due to a unique photoperiod compared to equatorial regions. At summer solstice in Interior Alaska, there is not a period of complete darkness. Heat requirements (DDs) for plants generally decrease with increasing photoperiods, resulting in fewer needed growing DDs to reach maturity (Juday et al. 2005). For some crops such as soybeans, even if the heating requirements were met, their biological triggers require specific lengths of daily darkness to mature making them and other dark-dependent plants virtually impossible for high latitudes agriculture (Van Veldhuizen and Knight 2004).

Another factor of consideration in using degree-days as determinants of crop feasibility is the humidity or timing of precipitation for a region. Growing DDs do not take into account humidity or precipitation factors which can affect the ability for degree-days to accurately project the maturation of a crop. Although the growing degree-days may equal or exceed heat requirements, a wet autumn may impede on the drying of the grain enough to make the crop not financially viable for mechanized harvest (Juday et al. 2005).

This makes it difficult to draw immediate or simple conclusions based on a single estimate of growing degree-days for each crop as each species or variety is affected differently by a myriad of variables including photoperiod. However, degree-days are widely considered good estimators of crop development (Juday et al. 2005). By using the best available data, scenario analysis can help look at a range of possible futures.

Attaining exact growing degree-day requirements for high latitude cultivars is a complex challenge. Previous efforts in summarizing literature about Interior Alaska cultivar degree-day requirements have found inconsistencies in the literature due to varying base temperature uses (Juday et al. 2005), a lack of high latitude cultivar growing degree-day resources (Sparrow et al. 2007; Hatch 2011) and inconsistencies with calculations concerning beginning and ending points.

Previous determined estimates of GDD values for high latitude specific cultivars from Juday et al. (2005) and Hatch (2010), point to the potential expansion of feasible crops; especially those that are currently marginally successful across the Arctic. Using multiple resources within the literature, Juday et al. (2005) selected annual crops that are currently produced or marginally produced in the Arctic region (above 60°N) with high economic potential including cereal grains, human foods and oilseeds (Table 3.15).

These previous studies found similar increases in growing degree-day values to the model presented here providing evidence that this model is a useful tool for modeling agriculturally specific degree-days at the 2km scale for Interior Alaska. Juday et al. (2005) projected that Fairbank Alaska may experience from 2025-2625 growing degrees-days from the years 2071 to 2090. Juday et al. (2005) concluded that Fairbanks would be suitable for peas (seed or processing), spring barley, oats, canola, potatoes, spring wheat, dry beans, sunflowers, alfalfa, red clover and timothy grass.

Hatch projected for the years 2097-2099 that the Fairbanks North Star Borough may experience between 1500 to more than 2301 growing degree-days (base °C). Hatch (2010) used a coefficient to decrease the growing season (spring 0°C to fall 0°C) estimating that agriculturalists use 70% of the total growing degree-days available, in an attempt to model agricultural specific DDs. Using this estimation Hatch (2011) determined that the Fairbanks North Star Borough would experience the same number

of growing degree-days as found in the Pacific Northwest (e.g. Western MT) of the United States by the end of the century and corn was expected to be a feasible crop by the 2090 decade.

Although Hatch (2011) made an attempt to limit the total seasonal growing degree-day totals for agriculturalists, neither of these analyses specified a definition of the agricultural growing season within the model. This model used specific temperature-based definitions to define the agriculturalist growing season in attempt to make projections more realistic to agriculturalists limitations that correspond to the topographical differences across the landscape. By the end of the century, this model produced more conservative and concise estimates than the previous two studies; projecting that the climate at the end of the century would experience 1839-2514 UDDs for early seeded field cultivars and 1549-2225 UDDs for late transplanted or cold sensitive vegetable crops. These ranges of values represent the entire model domain including mountain tops. Focusing on the FEF farm pixel, ranges decrease. For the FEF pixel there were 2330-2451 UDDs for seeded field crops and 2026-2163 UDDs for transplanted vegetable crops across all scenario ranges, making all crops in Table 3.14 and 3.15 feasible by 2090 including the currently marginal crops of canola, flax and sunflowers. It should be noted, however, that many of these marginal crops, can be

negatively affected if there is not enough moisture or too much moisture at inopportune periods of the growing season (Van Veldhuizen and Knight 2004).

Another crop that is produced marginally in the Interior that is expected to become feasible is corn. Corn is difficult to predict with only UDDs because there is not much literature on high latitude corn varieties UDD requirements. Furthermore, degree-days for corn are calculated with a base temperature of 10°C and the estimates in this model produced UDDs with a base temperature of °0C, making it difficult to compare values directly from the literature. Corn needs especially warm (10°C) soil temperatures to germinate and thrive (Neild and Newman 1987; Fraisse et al. 2012; ACE 2013) and the transplanted vegetable scenario in this analysis is most likely the best estimate for soils having reached 10° temperature since there has been longer amount of time to warm soil temperatures where the early seeded field crops can be seeded in cool soils directly after soils are tillable.

Marginal crops such as canola, corn and sunflowers will likely increase in success rates towards the end of the century. However the potentially biggest increases in economic and avenues in local food access opportunities will likely be in the extended periods of harvests for small diverse farms or CSAs and the increasing frequencies of cuttings of perennial forages (Sparrow et al. 2007). In a region that is mainly small-scale farms and gardens not hoping to expand quickly (Caster 2011), coupled with projections

that adaptation to a new crop can take 15-30 years (Sparrow et al. 2007), perhaps the focus for economic development and research should first focus on climate change effects on what is currently economically and culturally successful. Large-scale corn and canola just may not only be feasible due to a lack of infrastructure but also cultural values of the farmer. Large scale agricultural operations have been implemented in Alaska including efforts in milk and barley production. Most implementations have failed economically presumably because of a lack in state infrastructure, interest in farming, and competition from outside products. Efforts in research and institutional support should first focus on what is currently successful in Interior Alaska including small diversified farms. If farmers can capitalize on 4 more weeks of production successfully this, for example, could mean an increased number of spinach rotations or increased yields of winter squash by the end of the century. Longer-term planning should focus on identifying GDD requirements for high latitude crops and building infrastructure to support farming operations that are culturally appropriate in an uncertain future.

3.6 Conclusions

The model presented in this paper projected estimates degree-days within the specific confines of Interior Alaska growing season and was found to be in line with previous efforts to model crop feasibility. An increase of 33- 50% for early field and 38-

70% for late vegetable crop UDDs is expected across the model domain for a range of scenarios. The agricultural growing season is expected to increase equally in both the spring and fall resulting in a growing season increase of 19-28 days by the end of the century. The projected increase in heat energy is expected to make crops that are currently marginally successful such as corn, canola, flax and sunflowers, feasible by the end of the century. As there is potential for new crop opportunities, currently successful farming operations may benefit from an extra crop rotation or an increase of 2.5 to 4 weeks profitability. Increases in food security can be achieved if opportunities are capitalized upon but future planning will require culturally appropriate planning with institutional support.

3.7 Figures

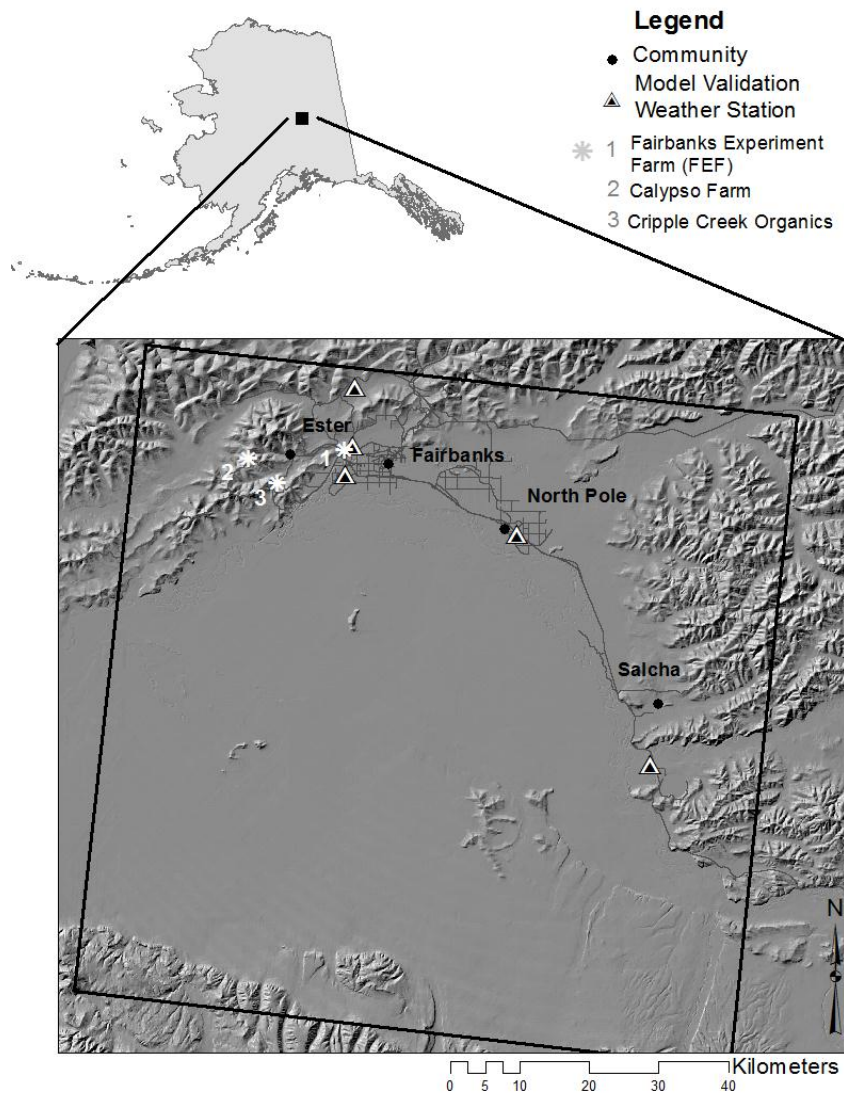


Figure 3.1 Model domain showing largest communities, validation weather station locations and farms with available observations used to check model outputs.

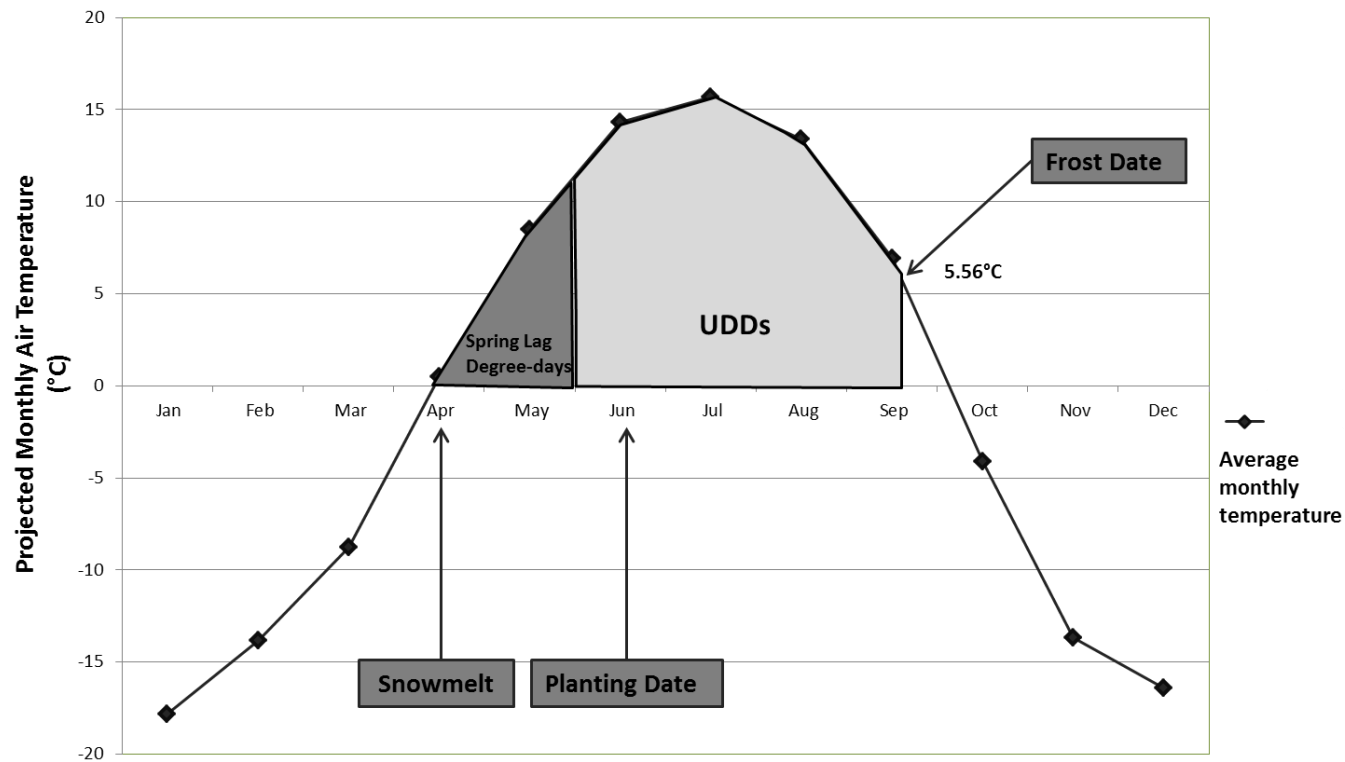


Figure 3.2 Visual depiction of model calculations for a late vegetable crop estimate. Presented is an average decadal temperature curve with secondary seasonal boundary estimates of snow melt, spring lag degree-day threshold, planting date and the temperature threshold for frost. The dark gray section displays an example of spring lag degree-day accumulation between snowmelt and planting date. The light gray section highlights the usable degree-days(UDDs) calculated in the usable growing season.

UDDs By Decade 2010-2090 Early - Directly Seeded Crops

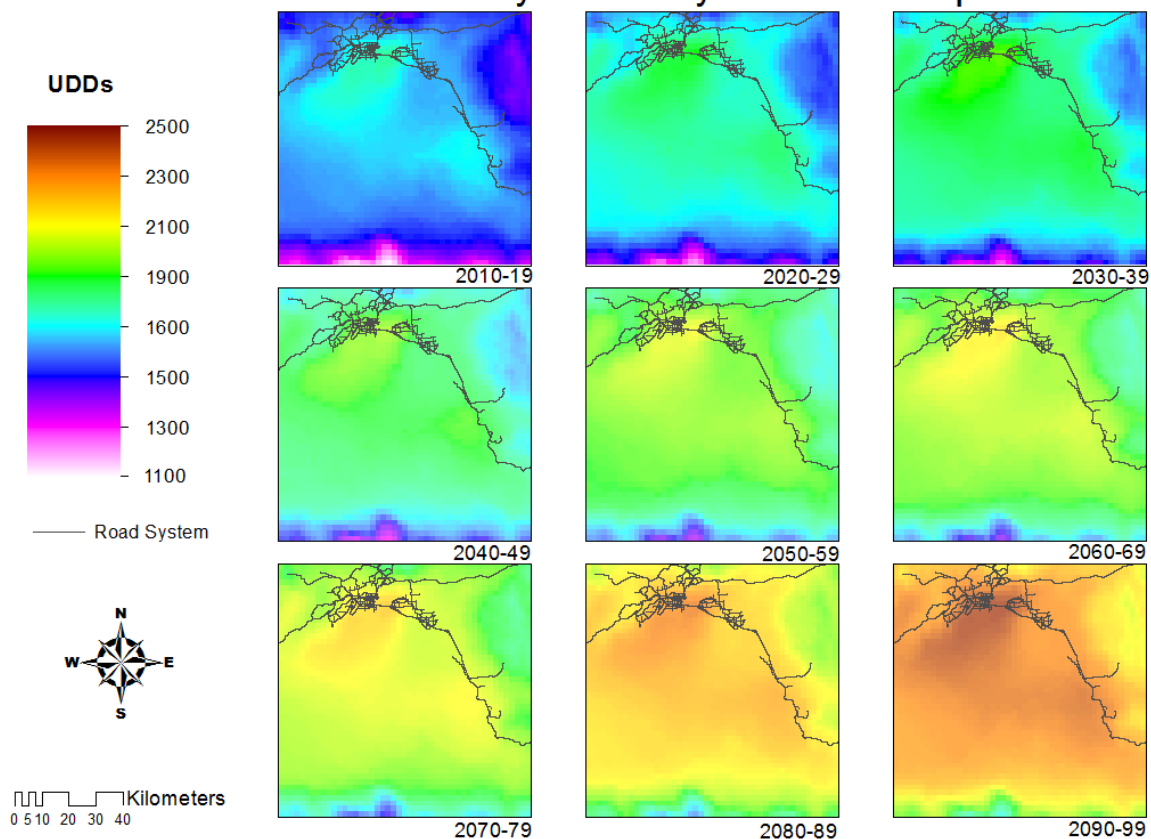


Figure 3.3 Projected average decadal UDDs for the early or directly seeded management scenario across model domain.

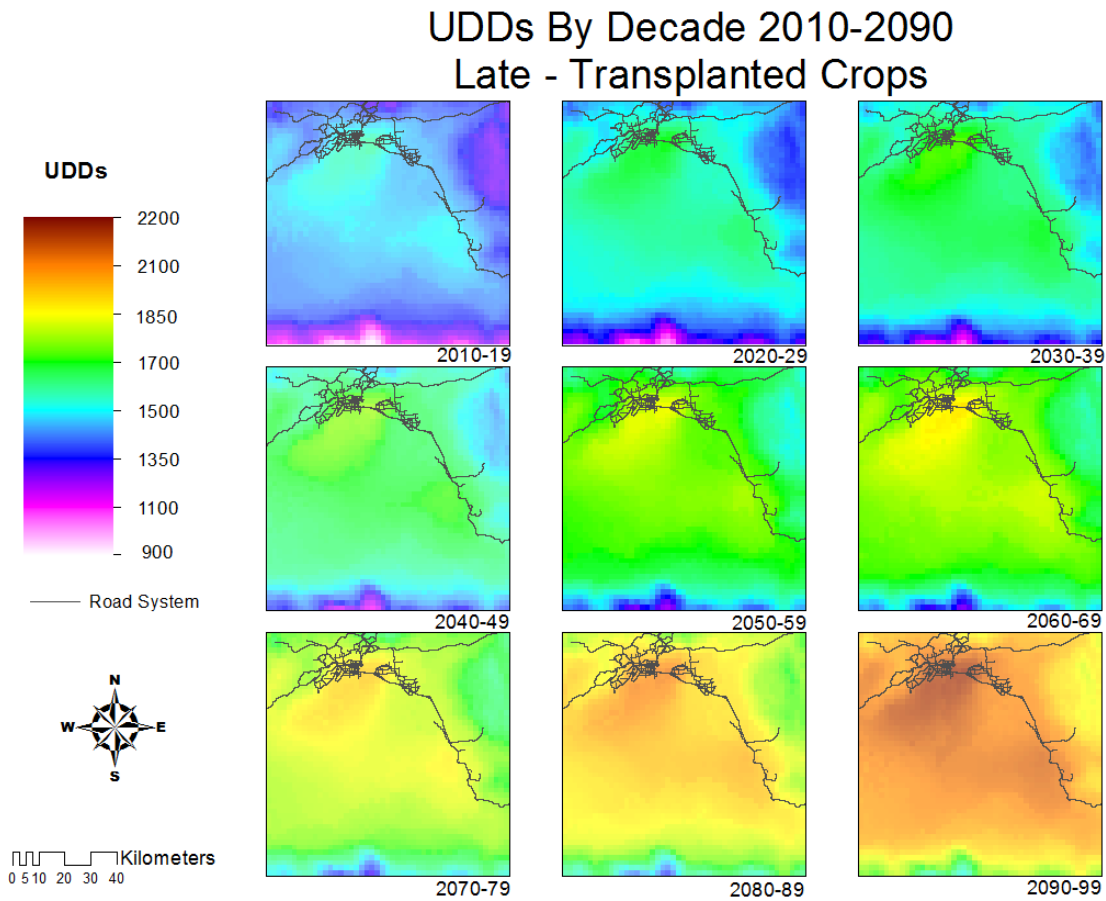


Figure 3.4 Projected average decadal UDDs for the late or transplant management scenario across model domain.

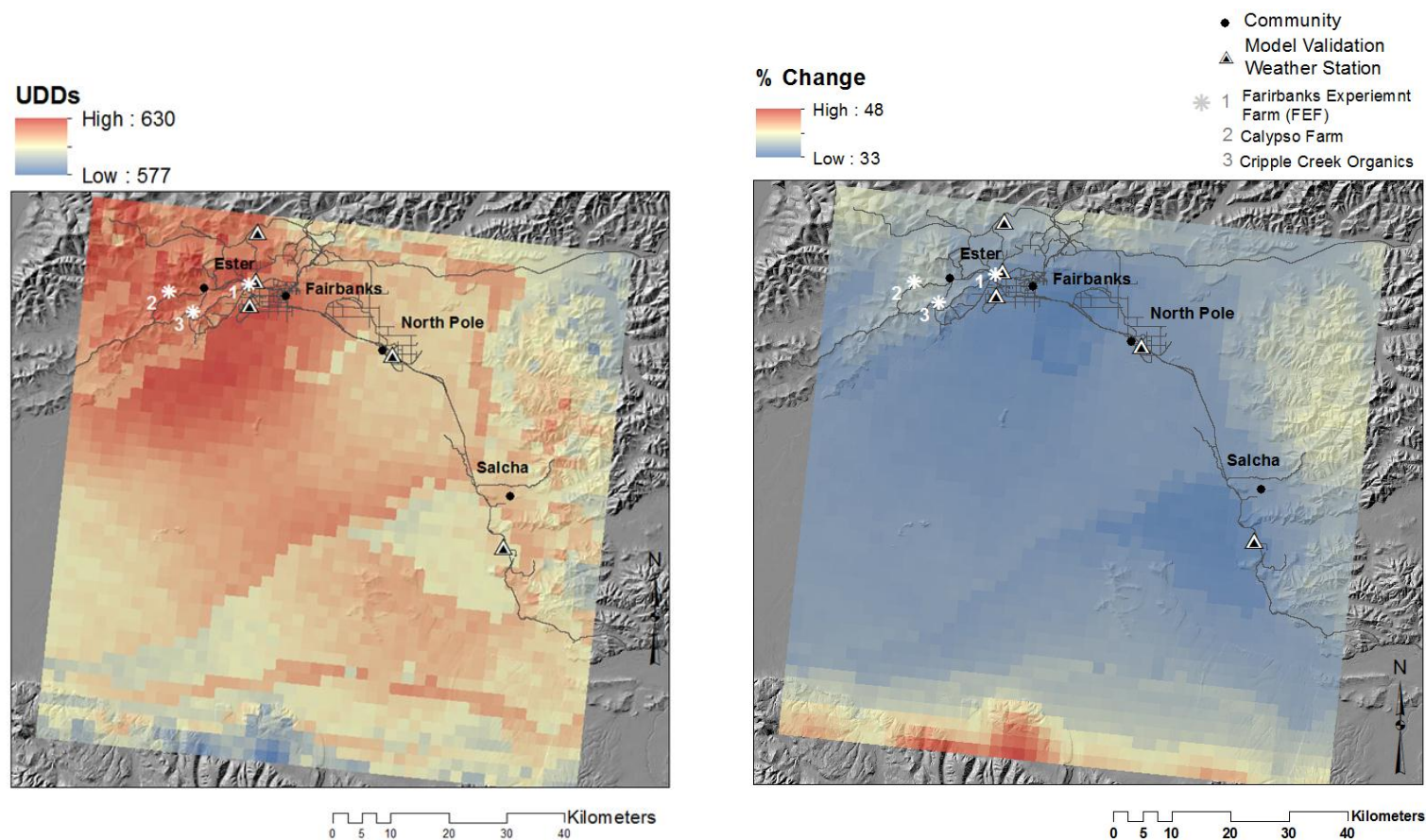


Figure 3.5 Total change and percent change in early crop usable degree-days (UDDs) across model domain. Left: change in usable degree-days (UDDs) across the model domain from decades 2010-19 to 2090-99 for the average field crop scenario. Right: percent change in UDDs across model domain from decades 2010-19 to 2090-99 for the average field crop scenario.

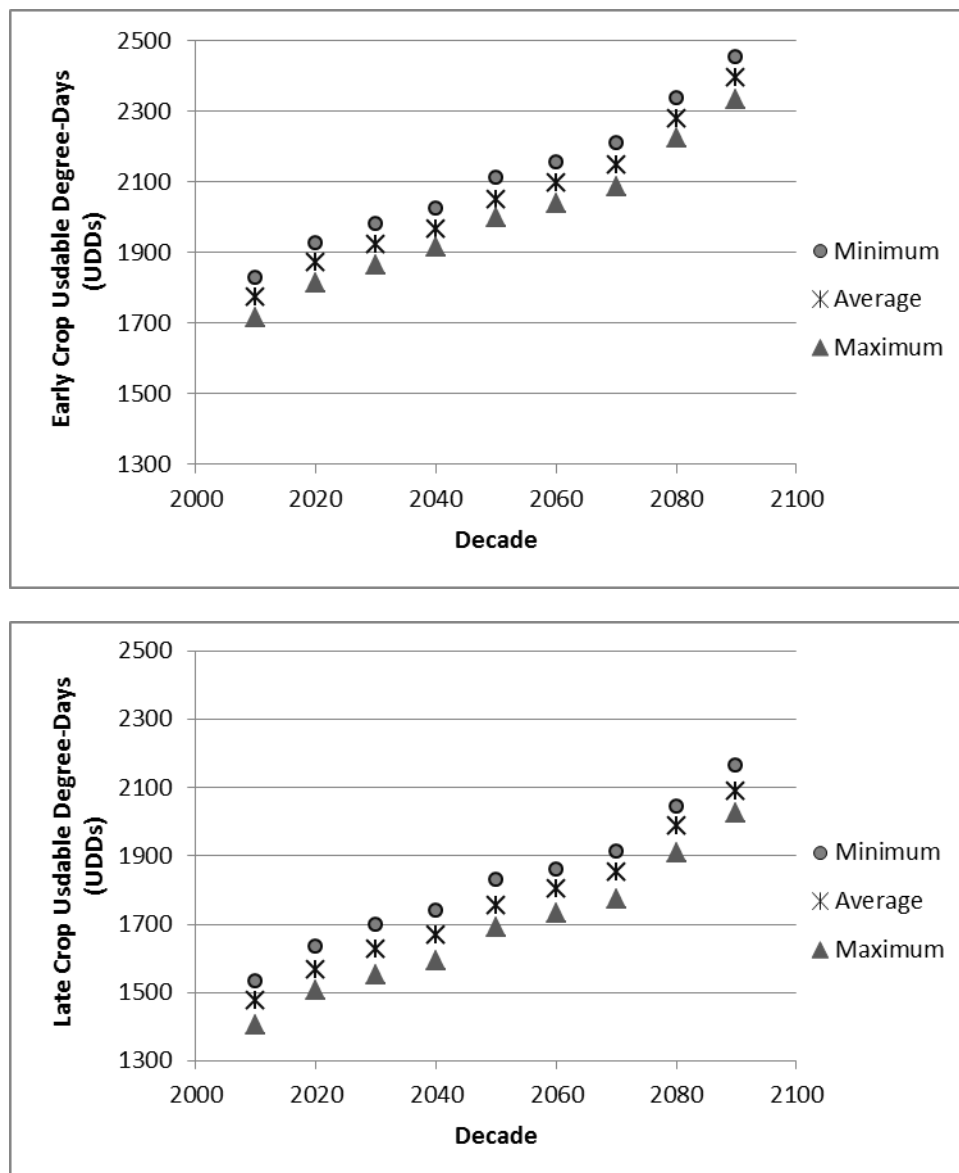


Figure 3.6 Projected usable degree-days (UDDs) for both the early and late crop management scenarios by decade for the FEF pixel. Minimum, average and maximum scenarios within management scenarios refer to the input variable spring lag determining the number of degree-days required to accumulate after snowmelt in order to determine planting date.

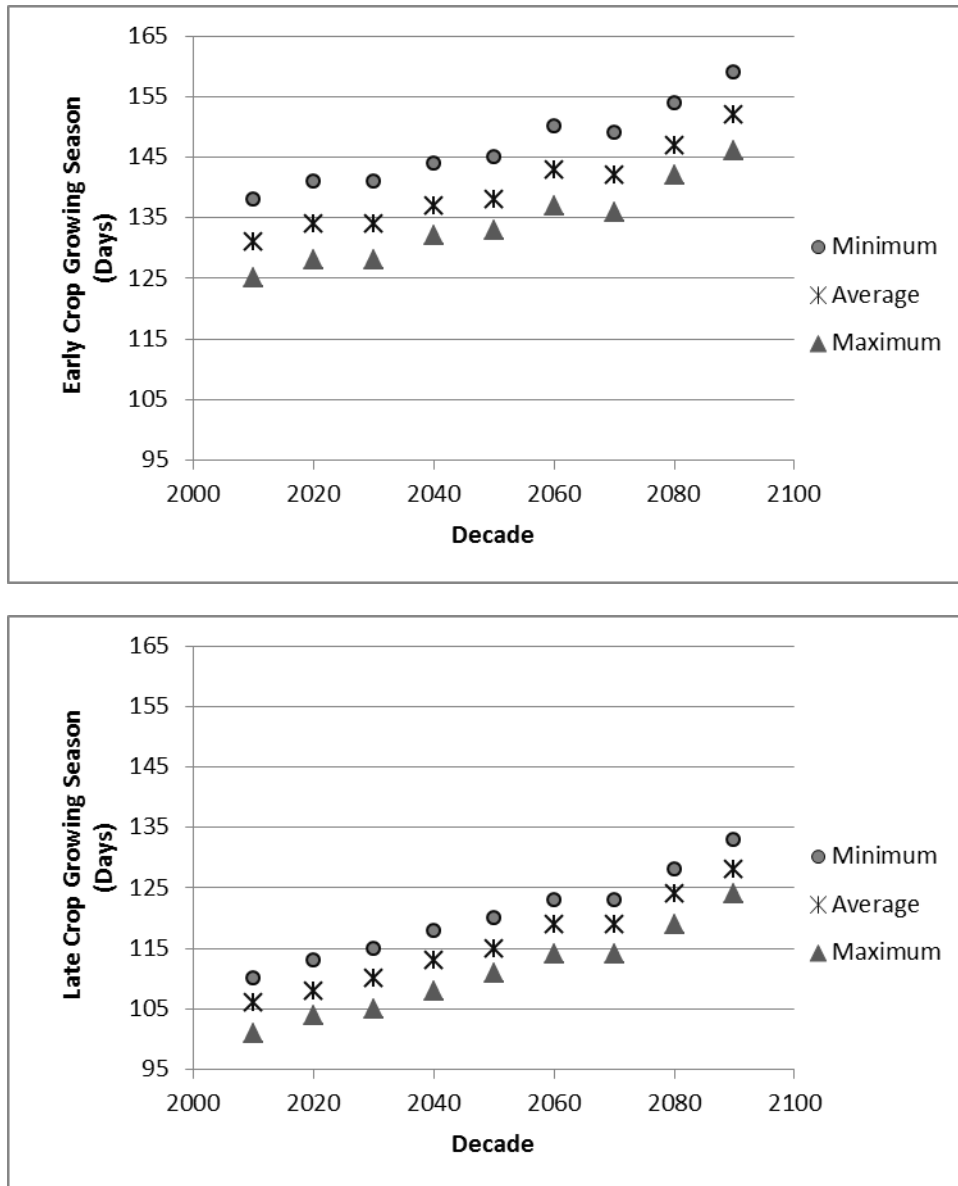


Figure 3.7 Projected lengths of growing season (days) for both the late and early crop management scenarios by decade for the FEF pixel. Minimum, average and maximum scenarios within management scenarios refer to the input variable spring lag determining the number of degree-days required to accumulate after snowmelt in order to determine planting date.

3.8 Tables

Table 3.1 Average annual (1981-2009) observed day of snowmelt compared to historical model output using downscaled historical climate data.

| Day of Snowmelt | College 5NW | College | Airport | North Pole | Salcha |
|--|----------------|---------|---------|---------------|------------|
| Observed Average Day of Snow Melt (30 year Average) | 24-Apr | 26-Apr | 24-Apr | 25- Apr | 26- Apr |
| CRU Modeled Average "Snow Melt" | 14-Apr | 12-Apr | 11-Apr | 11- Apr | 13- Apr |
| Modeled - Observed (Days) | 10 | 14 | 13 | 14 | 13 |
| Observed Degree-Days during discrepancy | 17 | 21 | 20 | 16 | 11 |

Table 3.2 Average annual (1981-2009) historical weather station observations compared to downscaled historical climate data model output dates for day of frost.

| Day of Frost | College 5NW | College | Airport | North Pole | Salcha |
|--|----------------|---------|---------|---------------|------------|
| Average Modeled CRU (historical) (30 year average) | 19-Sep | 20-Sep | 21-Sep | 17-Sep | 20- Sep |
| Observed 5.56°C (30 year average) | 22-Sep | 20-Sep | 23-Sep | 19-Sep | 19- Sep |
| Modeled – Observed (Days) | -3 | 0 | -2 | -2 | 1 |

Table 3.3 Average differences between historical model output and past FEF observations. Modeled values were taken from the pixel corresponding to the FEF. Values indicating a negative value signify that the modeled date was earlier than the farm observation or that the modeled UDD values undershot (were less than) the observed farm values. Both negative and positive (\pm) indicate that there were years within the comparison variable that were projected both before and after the observed date (or more or less UDDs) than observed at FEF.

| Model Outputs vs FEF Observations | Snowmelt Date (Days) | Early Crop Plant Date (Days) | Late Plant Date (Days) | Frost Date (Days) | Early Crop UDDs | Late Crop UDDs |
|--|-------------------------------------|---|---|----------------------------------|--------------------------------|-------------------------------|
| Minimum Spring Lag Scenario | -9 | -6 | -6 | ± 7 | 179 | 193 |
| Maximum Spring Lag Scenario | -9 | 6 | ± 4 | ± 7 | ± 85 | 59 |

Table 3.4 Calypso Farm pixel values compared to available years of farmer observations. Negative values indicate that the model projected the date or UDDs before or less than what was observed.

| Calypso Farm and Ecology Differences | Early Crop Plant Date (Days) | Late Crop Plant Date (Days) | Frost Date (Days) | Early Crop UDDs | Late Crop UDDs |
|---|---|--|----------------------------------|--------------------------------|---------------------------|
| 2005 – Minimum Scenario | 0 | -17 | -3 | 285 | 47 |
| 2009 – Minimum Scenario | 5 | 33 | 1 | 143 | -148 |
| 2005 – Maximum Scenario | 13 | 27 | -3 | 165 | 47 |
| 2009 – High Scenario | 17 | 42 | 1 | 34 | 277 |

Table 3.5 Cripple Creek Organics pixel values compared to available years of farmer observations. Negative values indicate that the model projected the date or UDDs before or less than what was observed.

| Cripple Creek Organics Differences | Early Crop Plant Date (Days) | Late Plant Date (Days) | Early Crop UDDs | Late Crop UDDs |
|---|-------------------------------------|-------------------------------|------------------------|-----------------------|
| 2007 – Minimum Scenario | -17 | -1 | 269 | 113 |
| 2008 – Minimum Scenario | -11 | N/A | 297 | 118 |
| 2009 – Minimum Scenario | -9 | N/A | 279 | 171 |
| 2007 – Maximum Scenario | -5 | 10 | 160 | -28 |
| 2008 – Maximum Scenario | 2 | N/A | 181 | -4 |
| 2009 – Maximum Scenario | 3 | N/A | 168 | 40 |

Table 3.6 Location and elevation of farms used for high elevation validation.

| | Latitude: | Longitude | Elevation (Meters) |
|--|------------------|------------------|---------------------------|
| Ester Weather Station GHCND: USC00502870 | 64.846 | -148.025 | 200 |
| Calypso Farm and Ecology Center | 64.840 | -148.133 | 1580 |
| Cripple Creek Organics | 64.808 | -148.063 | 855 |

Table 3.7 Summarized comparisons of modeled UDDs between the decades 2010-19 and 2090-99 across the 2208 pixels within the projection area of the model. Within both the early and late crop management scenarios the minimum, average and maximum scenarios are presented above. Scenarios refer to the model input spring lag; referring to the number of degree-days required to accrue to estimate planting date after snow melt. Differences represent the average, minimum and maximum change in planting date or growing season for each pixel from 2010 to 2090.

| Spring Lag Scenario: | Early Field UDDs: | 2010 Field UDD | 2090 Field UDD | Difference in Field UDDs | % Change in Field UDDs | Late Vegetable UDDs: | 2010 Vegetable UDD | 2090 Vegetable UDD | Difference | % Change in Vegetable UDDs |
|----------------------|-------------------|----------------|----------------|--------------------------|------------------------|----------------------|--------------------|--------------------|------------|----------------------------|
| Minimum: | Average | 1718 | 2327 | 608 | 35.5 | | 1431 | 2039 | 609 | 42.7 |
| | Min | 1259 | 1839 | 580 | 32.6 | | 969 | 1549 | 572 | 38.3 |
| | Max | 1890 | 2514 | 630 | 46.1 | | 1605 | 2225 | 634 | 59.9 |
| Average: | Average: | 1662 | 2271 | 610 | 36.8 | | 1363 | 1971 | 608 | 44.8 |
| | Min | 1209 | 1786 | 577 | 33.7 | | 909 | 1485 | 572 | 39.8 |
| | Max | 1832 | 2452 | 631 | 47.7 | | 1537 | 2161 | 637 | 63.4 |
| Maximum: | Average: | 1602 | 2210 | 609 | 38.1 | | 1293 | 1901 | 608 | 47.2 |
| | Min | 1149 | 1721 | 572 | 34.7 | | 835 | 1417 | 573 | 41.9 |
| | Max | 1771 | 2398 | 632 | 49.8 | | 1461 | 2085 | 638 | 69.7 |

Table 3.8 Modeled snowmelt and frost date changes from the decade 2010-19 to 2090-99 across model domain. Results represent the average, minimum, and maximum differences for all 2208 pixels within the projection area of the model. These parameters were consistent between both crop management scenarios.

| Snowmelt: | 2010 | 2090 | Difference By pixel (Days) | Day of Frost: | 2010 | 2090 | Difference by pixel (Days) |
|------------------|--------|--------|----------------------------------|----------------------|--------|--------|-------------------------------|
| Average: | 14-Apr | 3-Apr | -11 | | 18-Sep | 28-Sep | 10 |
| Min | 9-Apr | 28-Mar | -14 | | 12-Sep | 23-Sep | 9 |
| Max | 22-Apr | 8-Apr | -9 | | 21-Sep | 1-Oct | 11 |

Table 3.9 Modeled early crop planting date and growing season length comparisons between the decades of 2010 and 2090. Comparisons represent the differences from 2010-19 to 2090-99 across all of the 2208 pixels within the model domain. Scenarios refer to the model input spring lag; referring to the number of degree-days required to accrue to estimate planting date after snow melt. Differences represent the average, minimum and maximum change in planting date or growing season length from 2010 to 2090 for each pixel within the model domain.

| Spring Lab Scenario: | Early Crop Plant Date: | 2010 | 2090 | Difference by pixel (Days) | Early Crop Growing Season: | 2010 (Days) | 2090 (Days) | Difference by pixel (Days) |
|----------------------|------------------------|--------|--------|----------------------------|----------------------------|-------------|-------------|----------------------------|
| Minimum | Average: | 8-May | 27-Apr | 11 | | 133 | 154 | 21 |
| | Min | 4-May | 20-Apr | 9 | | 117 | 143 | 19 |
| | Max | 18-May | 3-May | 15 | | 139 | 159 | 26 |
| Average | Average: | 15-May | 3-May | 12 | | 126 | 148 | 22 |
| | Min | 12-May | 27-Apr | 10 | | 110 | 136 | 19 |
| | Max | 25-May | 10-May | 15 | | 132 | 153 | 26 |
| Maximum | Average: | 21-May | 9-May | 12 | | 120 | 142 | 22 |
| | Min | 18-May | 4-May | 10 | | 103 | 129 | 19 |
| | Max | 1-Jun | 17-May | 16 | | 126 | 147 | 27 |

Table 3.10 Modeled late crop planting date and growing season length comparisons between the decades of 2010 and 2090. Comparisons represent the differences from 2010-19 to 2090-99 across all of the 2208 pixels within the model domain. Scenarios refer to the model input spring lag; referring to the number of degree-days required to accrue to estimate planting date after snow melt. Differences represent the average, minimum and maximum change in planting date or growing season length from 2010 to 2090 for each pixel within the model domain.

| Spring Lag Scenario: | Late Crop Plant Date: | 2010 | 2090 | Difference by pixel (Days) | Late Crop Growing Season: | 2010 (Days) | 2090 (Days) | Difference by pixel (Days) |
|----------------------|-----------------------|--------|--------|----------------------------|---------------------------|-------------|-------------|----------------------------|
| Minimum | Average: | 5-Jun | 22-May | 13 | | 105 | 128 | 23 |
| | Min | 1-Jun | 19-May | 11 | | 86 | 114 | 20 |
| | Max | 18-Jun | 1-Jun | 17 | | 112 | 134 | 28 |
| Average | Average: | 10-Jun | 27-May | 13 | | 100 | 124 | 23 |
| | Min | 6-Jun | 24-May | 11 | | 81 | 109 | 21 |
| | Max | 23-Jun | 6-Jun | 17 | | 107 | 130 | 28 |
| Maximum | Average: | 15-Jun | 1-Jun | 14 | | 96 | 119 | 26 |
| | Min | 10-Jun | 29-May | 11 | | 75 | 104 | 25 |
| | Max | 29-Jun | 11-Jun | 18 | | 103 | 125 | 26 |

Table 3.11 Summarized sensitivity of the model to change in the variable snowmelt. Negative results indicate the change in model output produced values less or earlier than the original value from the zero change model run.

| Snowmelt Alteration Intervals (°C): | -5 | -3 | -1 | 0 | 1 | 3 | 5 |
|--|-------|-------|-------|---|-------|-------|-------|
| Snowmelt (°C) Input | -5 | -3 | -1 | 0 | 1 | 3 | 5 |
| Change in Snowmelt Date (Days) | 15 | 9 | 3 | 0 | -3 | -10 | -16 |
| Change in Early Crop Plant Date (Days) | -5 | -2 | -1 | 0 | -1 | -3 | -6 |
| Change in Late Crop Plant Date (Days) | -2 | -1 | 0 | 0 | 0 | -1 | -3 |
| Change in Early Crop UDDs | 39 | 15 | 7 | 0 | 8 | 18 | 47 |
| Change Late Crop UDDs | 28 | 14 | 0 | 0 | 1 | 6 | 42 |
| % Change Early Crop UDDs | 2.13% | 0.82% | 0.38% | | 0.44% | 0.98% | 2.57% |
| % Change Late Crop UDDs | 1.83% | 0.91% | 0.00% | | 0.07% | 0.39% | 2.74% |

Table 3.12 Summarized sensitivity of the model to change in the variable frost date estimator. Negative results indicate the change in model output produced values less or earlier than the original value from the zero change model run.

| Frost Alteration Interval (°C): | -5 | -3 | -1 | 0 | 1 | 3 | 5 |
|----------------------------------|--------|--------|--------|------|-------|-------|-------|
| Temperature (°C) Input | 0.56 | 2.56 | 4.56 | 5.56 | 6.56 | 8.56 | 10.56 |
| Change in Frost Date Crop (Days) | -13 | -8 | -3 | 0 | 3 | 10 | 17 |
| Change in Early Crop UDDs | -41 | -33 | -14 | 0 | 19 | 68 | 142 |
| Change in Late Crop UDDs | -41 | -33 | -14 | 0 | 19 | 68 | 142 |
| % Change Early Crop UDDs | -2.24% | -1.81% | -0.77% | | 1.04% | 3.72% | 7.77% |
| % Change Late Crop UDDs | -2.67% | -2.15% | -0.91% | | 1.24% | 4.44% | 9.26% |

Table 3.13 Summarized sensitivity of the model to change in the variable spring lag degree-days. Negative results indicate the change in model output produced values less or earlier than the original value from the zero change model run.

| Spring Lag DD % Alteration: | -50% | -30% | -10% | 0% | 10% | 30% | 50% |
|-----------------------------------|---------|--------|--------|-----|-------|-------|--------|
| Field DDs Input | 40 | 56 | 72 | 80 | 88 | 104 | 120 |
| Crop DDs Input | 200 | 280 | 360 | 400 | 440 | 520 | 600 |
| Change in Early Plant Date (Days) | 7 | 4 | 1 | 0 | -1 | -3 | -44 |
| Change in Late Plant Date (Days) | 16 | 9 | 3 | 0 | -3 | -8 | -107 |
| Change in Early UDDs | -45 | -27 | -8 | 0 | 7 | 23 | 39 |
| Change in Late UDDs | -202 | -120 | -42 | 0 | 43 | 118 | 212 |
| % Change Early Crop UDDs | -2.47% | -1.48% | -0.44% | | 0.38% | 1.26% | 2.14% |
| % Change Late Crop UDDs | -13.55% | -8.05% | -2.82% | | 2.88% | 7.91% | 14.22% |

Table 3.14 Required growing degree-days for cultivar maturity from Juday et al. (2005).

| Crop | Growing degree-days (0°C base) |
|-----------------------------|---|
| Peas (green for processing) | 1000 |
| Spring Barley | 1200-1500 |
| Peas (for seed) | 1500-1700 |
| Oats | 1300-1700 |
| Canola | 1350-1550 |
| Spring wheat | 1400-1650 |
| Sunflowers (for seed) | 1800-2000 |

Table 3.15 Degree-Day requirements to reach maturity from Miller et al (2001).

| Crop | Degree-Days (0°C) to reach maturity |
|-----------------------------|--|
| Barley | 1269-1522 |
| Wheat (Hard Red) | 1538-1665 |
| Oat | 1483-1738 |
| Canary Seed | 1342-1535 |
| Flax | 1603-1801 |
| Canola (<i>B. napus</i>) | 1432-1557 |
| Canola (<i>B rapa</i>) | 1249-1382 |
| Mustard (<i>B juncea</i>) | 1509-1610 |
| Mustard (<i>S. alba</i>) | 1521-1625 |
| Chick Pea Desi | 1679-1803 |
| Lentil | 1740-1876 |
| Pea | 1527-1686 |
| Sunflower | 1780-1972 |

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Chapter 4

Conclusions

4.1 Chapter Synthesis

4.1.1 Chapter 2

Chapter 2 field measurements identified soil temperature to be significantly cooler than air temperature in the spring, but was not found to be the single driving factor in establishing planting dates in Interior Alaska. Two management scenarios were defined for degree-day analysis – early and late planting scenarios. These two scenarios were developed to include farming practices that (1) result in direct seeding of crops with low base temperature requirements and that handle cooler soil and air temperatures, and (2) result in transplants being introduced later in the season due to higher base temperature requirements for plant growth and development. Within these two management systems the effects of crop canopy structure on soil heat accumulation were compared and found to have inconsistent effects on seasonal soil energy accumulation at the 5cm depth. Furthermore, crop canopy structure was found to lack any different cooling effects on soil energy accumulation at the 15cm depth.

Spring heat accumulation (i.e., degree-days, DDs) for both surface air and soil temperature were found to be significantly different at the time of planting. There were 260 and 480 DDs that accumulated at the surface before crops were planted in the spring for the early and late management groups, respectively. This reinforced the

notion that relying solely on air temperature as a predictor of plant growth at high-latitudes can exaggerate heat accumulation estimations if soil temperature, moisture and air temperature minimums are ignored. Finally, to refine the estimation of heat accumulation that is actually available for farming practices while maintaining the useful metric of degree-days, usable degree-days (UDDs) were defined as the DD accumulation between planting date and first frost.

4.1.2 Chapter 3

Chapter 3 modeling activities developed a tool that projects UDDs for the two management scenarios (early and late) through the end of the century. Modeled results suggest that changes in UDDs through this century may increase 570- 640 UDDs across the simulation domain. As a result estimates of the usable growing season length may increase by 19-28 calendar days with the increase split equally on either end of the growing season. These results imply economic opportunity for Interior agriculturalists and the potential for increased rates of success with currently marginal crops such as canola, sunflowers and flax.

Limits to the growing season for Interior Alaskan agriculturalists are not simple to define. The day a farmer can plant is determined by a complex combination of fluctuating variables that are based in both bio-physical and socio-economic realms. With a lack of data for both realms, the modeling tool developed in this research used farmer observations to define the beginning of the growing season in an attempt to

summarize all variables influencing planting date. This estimate uses the climate variable with the highest certainty of all projected climate variables: temperature. Modeling tools like the one presented in this thesis are not to be used as predictors of future conditions at specific locations, but as tools to explore future possibilities and scenarios.

4.2 Thesis Synthesis and Recommendations

As this model has proven to be a good start in defining the future growing conditions of Interior agriculturalists to the end of the century, expanding upon these efforts could provide important insight for not only Interior Alaska, but perhaps the entire State of Alaska and similar regions of the Arctic. Here I recommend ways to improve upon the modeling capabilities for agricultural purposes in Interior Alaska.

First, more diverse, extensive, and consistent data must be collected for agricultural systems throughout Alaska. If the effects of topography and management preferences could be documented, then researchers can begin to include and verify that the entire range of growing capabilities are considered in modeling efforts.

Second, data collection efforts cannot be placed on the farmer's shoulders alone. Maintaining and creating healthy working relationships between the farmer and researcher is an important aspect of data collection. In order to develop a working citizen science data collection environment, I advise that weather stations be maintained by the research institution so as not to add work to a farmer's complex

schedule; clear outlines be set for what data is needed, and the agriculturalist's community research needs be of first priority.

Third, the model results require further interpretation and analysis to prove useful in the decision making process. As the model results have suggested that new crops may become feasible in the coming decades, this does not mean that these crops will be economically successful at conventionally large scales or that the farmers and consumers themselves will welcome the change to a new large cash crop system in The Last Frontier. The increased feasibility of these new crops, such as canola or corn, will in some ways not be a new event in Alaska's agricultural history. Past agricultural efforts highlight the fact that just because the biophysical boundaries point toward success, does not guarantee large-scale economic success. Large-scale efforts in barley and milk production in Alaska have failed in the past not because of biophysical boundaries, but because of socio-economic complications (Davies 2008). For example, barley was found to be twice as productive (on a per acre basis) in Delta Junction, Alaska as compared to the Great Plains (Davies 2008); however lack of infrastructure, export capabilities, fluctuating prices and institutional support led to severely limiting challenges for large-scale barley production success across Alaska (Davies 2008).

This suggests that the success of new crops at larger production scales would be highly dependent on the capacity of institutions and investors to support a fluctuating agriculture sector. If corn can be grown, it must also have a place to be processed, an

inexpensive export route and available market. One possible indirect outcome of climate change that could help enhance these requirements may arise due to the projected northward movement of cash crop feasibility. This shift of crop feasibility could perhaps increase the likelihood that a market and supporting infrastructure move closer to Alaska making the connection to export markets an easier task.

Seasonal variability throughout the century may also pose challenges for future agricultural feasibility. Increases in season length and UDDs to the end of the century, although changing directionally, is expected to exhibit considerable variability from year to year. This seasonal fluctuation in growing conditions infers that farmers will need to include flexibility into the food system by, for example, focusing on planting multiple diverse crops each season to assure success, creating local avenues for selling products quickly in case of unexpected weather events, etc.

Finally, the potential for new crops should certainly be further investigated within the context of scenarios and crop trials, but a more important focus should be directed to research and planning efforts on the farms and crops that are currently experiencing the most economic success and gaining the most consumer support. Interior Alaska has many small diversified farms and community supported agriculture (CSA) systems that are gaining traction in summer produce markets and many report the lack of interest in expanding in size (Caster 2011). Extensions in growing seasons could mean increased economic opportunity for these farms by providing up to 4 more

weeks of profitability, and the potential for an increased number of crop rotations or harvests. Focusing on how these farms may be affected and what makes them successful currently could provide opportunities for increased food security and diversification of local products in the lengthening summer months.

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